Cengage

TENTH EDITION

CHEMISTRY
FOR TODAY
GENERAL, ORGANIC, AND BIOCHEMISTRY

SEAGER | SLABAUGH | HANSEN

PERIODIC TABLE OF THE ELEMENTS

KEY

79 — Atomic number
Au — Symbol
Gold — Name
197.0 — Atomic weight (rounded to four significant figures)

- 🟥 Metals
- 🟦 Metalloids
- 🟩 Nonmetals, noble gases

Group number, IUPAC system — (1)
Group number, U.S. system — IA
Period number — 2
Group designation — (2) IIA

Period	(1) IA	(2) IIA	(3) IIIB	(4) IVB	(5) VB	(6) VIB	(7) VIIB	(8)	(9) VIIIB	(10)	(11) IB	(12) IIB	(13) IIIA	(14) IVA	(15) VA	(16) VIA	(17) VIIA	Noble Gases (18) VIIIA
1	🟩 1 **H** Hydrogen 1.008																	🟩 2 **He** Helium 4.003
2	🟥 3 **Li** Lithium 6.94	🟥 4 **Be** Beryllium 9.012											🟦 5 **B** Boron 10.81	🟩 6 **C** Carbon 12.01	🟩 7 **N** Nitrogen 14.01	🟩 8 **O** Oxygen 16.00	🟩 9 **F** Fluorine 19.00	🟩 10 **Ne** Neon 20.18
3	🟥 11 **Na** Sodium 22.99	🟥 12 **Mg** Magnesium 24.31											🟥 13 **Al** Aluminum 26.98	🟦 14 **Si** Silicon 28.09	🟩 15 **P** Phosphorus 30.97	🟩 16 **S** Sulfur 32.06	🟩 17 **Cl** Chlorine 35.45	🟩 18 **Ar** Argon 39.95
4	🟥 19 **K** Potassium 39.10	🟥 20 **Ca** Calcium 40.08	🟥 21 **Sc** Scandium 44.96	🟥 22 **Ti** Titanium 47.87	🟥 23 **V** Vanadium 50.94	🟥 24 **Cr** Chromium 52.00	🟥 25 **Mn** Manganese 54.94	🟥 26 **Fe** Iron 55.85	🟥 27 **Co** Cobalt 58.93	🟥 28 **Ni** Nickel 58.69	🟥 29 **Cu** Copper 63.55	🟥 30 **Zn** Zinc 65.38	🟥 31 **Ga** Gallium 69.72	🟦 32 **Ge** Germanium 72.63	🟦 33 **As** Arsenic 74.92	🟩 34 **Se** Selenium 78.96	🟩 35 **Br** Bromine 79.90	🟩 36 **Kr** Krypton 83.80
5	🟥 37 **Rb** Rubidium 85.47	🟥 38 **Sr** Strontium 87.62	🟥 39 **Y** Yttrium 88.91	🟥 40 **Zr** Zirconium 91.22	🟥 41 **Nb** Niobium 92.91	🟥 42 **Mo** Molybdenum 95.96	🟥 43 **Tc** Technetium (98)	🟥 44 **Ru** Ruthenium 101.1	🟥 45 **Rh** Rhodium 102.9	🟥 46 **Pd** Palladium 106.4	🟥 47 **Ag** Silver 107.9	🟥 48 **Cd** Cadmium 112.4	🟥 49 **In** Indium 114.8	🟥 50 **Sn** Tin 118.7	🟦 51 **Sb** Antimony 121.8	🟦 52 **Te** Tellurium 127.6	🟩 53 **I** Iodine 126.9	🟩 54 **Xe** Xenon 131.3
6	🟥 55 **Cs** Cesium 132.9	🟥 56 **Ba** Barium 137.3	🟥 57 **La** Lanthanum 138.9	🟥 72 **Hf** Hafnium 178.5	🟥 73 **Ta** Tantalum 180.9	🟥 74 **W** Tungsten 183.8	🟥 75 **Re** Rhenium 186.2	🟥 76 **Os** Osmium 190.2	🟥 77 **Ir** Iridium 192.2	🟥 78 **Pt** Platinum 195.1	🟥 79 **Au** Gold 197.0	🟥 80 **Hg** Mercury 200.6	🟥 81 **Tl** Thallium 204.4	🟥 82 **Pb** Lead 207.2	🟥 83 **Bi** Bismuth 209.0	🟥 84 **Po** Polonium (209)	🟦 85 **At** Astatine (210)	🟩 86 **Rn** Radon (222)
7	🟥 87 **Fr** Francium (223)	🟥 88 **Ra** Radium (226)	🟥 89 **Ac** Actinium (227)	🟥 104 **Rf** Rutherfordium (265)	🟥 105 **Db** Dubnium (268)	🟥 106 **Sg** Seaborgium (271)	🟥 107 **Bh** Bohrium (270)	🟥 108 **Hs** Hassium (277)	🟥 109 **Mt** Meitnerium (276)	🟥 110 **Ds** Darmstadtium (281)	🟥 111 **Rg** Roentgenium (280)	🟥 112 **Cn** Copernicium (285)	🟥 113 **Nh** Nihonium (284)	🟥 114 **Fl** Flerovium (289)	🟥 115 **Mc** Moscovium (288)	🟥 116 **Lv** Livermorium (293)	🟩 117 **Ts** Tennessine (294)	🟩 118 **Og** Oganesson (294)

Mass numbers in parentheses are the most stable radioactive isotope.

Period														
6	🟥 58 **Ce** Cerium 140.1	🟥 59 **Pr** Praseodymium 140.9	🟥 60 **Nd** Neodymium 144.2	🟥 61 **Pm** Promethium (145)	🟥 62 **Sm** Samarium 150.4	🟥 63 **Eu** Europium 152.0	🟥 64 **Gd** Gadolium 157.3	🟥 65 **Tb** Terbium 158.9	🟥 66 **Dy** Dysprosium 162.5	🟥 67 **Ho** Holmium 164.9	🟥 68 **Er** Erbium 167.3	🟥 69 **Tm** Thulium 168.9	🟥 70 **Yb** Ytterbium 173.0	🟥 71 **Lu** Lutetium 175.0
7	🟥 90 **Th** Thorium 232.0	🟥 91 **Pa** Protactinium 231.0	🟥 92 **U** Uranium 238.0	🟥 93 **Np** Neptunium (237)	🟥 94 **Pu** Plutonium (244)	🟥 95 **Am** Americium (243)	🟥 96 **Cm** Curium (247)	🟥 97 **Bk** Berkelium (247)	🟥 98 **Cf** Californium (251)	🟥 99 **Es** Einsteinium (252)	🟥 100 **Fm** Fermium (257)	🟥 101 **Md** Mendelevium (258)	🟥 102 **No** Nobelium (259)	🟥 103 **Lr** Lawrencium (262)

TENTH EDITION

Chemistry for Today

General, Organic, and Biochemistry

Spencer L. Seager
Weber State University

Michael R. Slabaugh
University of South Dakota
Weber State University

Maren S. Hansen
University of South Dakota

Cengage

Australia • Brazil • Canada • Mexico • Singapore • United Kingdom • United States

This is an electronic version of the print textbook. Due to electronic rights restrictions, some third party content may be suppressed. Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. The publisher reserves the right to remove content from this title at any time if subsequent rights restrictions require it. For valuable information on pricing, previous editions, changes to current editions, and alternate formats, please visit www.cengage.com/highered to search by ISBN#, author, title, or keyword for materials in your areas of interest.

Important Notice: Media content referenced within the product description or the product text may not be available in the eBook version.

***Chemistry for Today: General, Organic, and Biochemistry,* 10th Edition**
Spencer L. Seager, Michael R. Slabaugh, Maren S. Hansen

SVP, Higher Education: Erin Joyner

VP, Higher Education: Julia Caballero

Product Director: Maureen McLaughlin

Product Manager: Roxanne Wang

Product Assistant: Nellie Mitchell

Learning Designer: Susan Pashos

Content Manager: Meaghan Ford

Digital Delivery Lead: Beth McCracken

Director, Marketing: Jennifer Fink

Marketing Manager: Andrew Stock

IP Analyst: Ann Hoffman

IP Project Manager: Kelli Besse

Designer: Lizz Anderson

Cover Image Source: iStock.com/xubingruo

Compositor: MPS Limited

Last three editions, as applicable: © 2018, © 2014, © 2011

© 2022 Cengage Learning, Inc. ALL RIGHTS RESERVED.

WCN: 02-300

No part of this work covered by the copyright herein may be reproduced or distributed in any form or by any means, except as permitted by U.S. copyright law, without the prior written permission of the copyright owner.

For product information and technology assistance, contact us at **Cengage Customer & Sales Support, 1-800-354-9706 or support.cengage.com.**

For permission to use material from this text or product, submit all requests online at **www.copyright.com.**

Library of Congress Control Number: 2020919516

ISBN: 978-0-357-45338-4

Cengage
200 Pier 4 Boulevard
Boston, MA 02210
USA

Cengage is a leading provider of customized learning solutions with employees residing in nearly 40 different countries and sales in more than 125 countries around the world. Find your local representative at: **www.cengage.com.**

To learn more about Cengage platforms and services, register or access your online learning solution, or purchase materials for your course, visit **www.cengage.com.**

Printed in the United States of America
Print Number: 01 Print Year: 2021

This 10th edition is dedicated to the memory of Wayne Aprill, a high school science teacher who touched the lives of everyone around him; students, family and many good friends.

About the Authors

Spencer L. Seager

Spencer L. Seager retired from Weber State University in 2013 after serving for 52 years as a chemistry department faculty member. He served as department chairman from 1969 until 1993. He taught general and physical chemistry at the university. He was also active in projects designed to help improve chemistry and other science education in local elementary schools. He received his B.S. in chemistry and Ph.D. in physical chemistry from the University of Utah.

Michael R. Slabaugh

Michael R. Slabaugh is an adjunct professor at the University of South Dakota and at Weber State University, where he teaches the yearlong sequence of general chemistry, organic chemistry, and biochemistry. He received his B.S. degree in chemistry from Purdue University and his Ph.D. degree in organic chemistry from Iowa State University. His interest in plant alkaloids led to a year of postdoctoral study in biochemistry at Texas A&M University. His current professional interests are chemistry education and community involvement in science activities, particularly the State Science and Engineering Fair in Utah. He also enjoys the company of family, hiking in the mountains, and fishing in local streams.

Maren S. Hansen

Maren S. Hansen has been a science teacher at West High School, where she taught honors biology. She has also taught AP biology and biology in the International Baccalaureate Program. She received her B.A. and master of education degrees from Weber State University. Her professional interests have focused upon helping students participate in Science Olympiad and Science Fair. Other interests include adventure travel, mountain hiking, gardening, and the company of friends and family. She hopes to share her love of science with her two children. She currently serves as an adjunct professor at the University of South Dakota, where she teaches online courses in general chemistry, elementary organic chemistry, and elementary biochemistry.

Brief Contents

Chapter 1
Matter, Measurements, and Calculations 2

Chapter 2
Atoms and Molecules 46

Chapter 3
Electronic Structure and the Periodic Law 70

Chapter 4
Forces between Particles 96

Chapter 5
Chemical Reactions 138

Chapter 6
The States of Matter 164

Chapter 7
Solutions and Colloids 198

Chapter 8
Reaction Rates and Equilibrium 236

Chapter 9
Acids, Bases, and Salts 260

Chapter 10
Radioactivity and Nuclear Processes 304

Chapter 11
Organic Compounds: Alkanes 330

Chapter 12
Unsaturated Hydrocarbons 372

Chapter 13
Alcohols, Phenols, and Ethers 408

Chapter 14
Aldehydes and Ketones 446

Chapter 15
Carboxylic Acids and Esters 478

Chapter 16
Amines and Amides 510

Chapter 17
Carbohydrates 546

Chapter 18
Lipids 582

Chapter 19
Proteins 614

Chapter 20
Enzymes 646

Chapter 21
Nucleic Acids and Protein Synthesis 672

Chapter 22
Nutrition and Energy for Life 706

Chapter 23
Carbohydrate Metabolism 736

Chapter 24
Lipid and Amino Acid Metabolism 762

Chapter 25
Body Fluids 792

Contents

Chapter 1

Matter, Measurements, and Calculations 2

- **1.1** What Is Matter? *3*
- **1.2** Properties and Changes *4*
- **1.3** A Model of Matter *7*
- **1.4** Classifying Matter *9*
- **1.5** Measurement Units *13*
- **1.6** The Metric System *13*
- **1.7** Large and Small Numbers *19*
- **1.8** Significant Figures *23*
- **1.9** Using Units in Calculations *28*
- **1.10** Calculating Percentages *30*
- **1.11** Density *32*
  - Concept Summary *36*
  - Key Terms and Concepts *37*
  - Key Equations *37*
  - Exercises *38*
  - Additional Exercises *44*
  - Chemistry for Thought *44*
  - **Health Career Focus** *2*
  - **ENVIRONMENTAL CONNECTIONS 1.1** A Central Science *5*
  - **HEALTH CONNECTIONS 1.1** Effects of Temperature on Body Functions *19*
  - **STUDY TOOLS 1.1** Help with Calculations *32*
  - **HEALTH CONNECTIONS 1.2** Choose Wisely for Health Information *34*
  - **Health Career Description** *35*

Chapter 2

Atoms and Molecules 46

- **2.1** Symbols and Formulas *47*
- **2.2** Inside the Atom *49*
- **2.3** Isotopes *51*
- **2.4** Relative Masses of Atoms and Molecules *52*
- **2.5** Isotopes and Atomic Weights *55*
- **2.6** Avogadro's Number: The Mole *57*
- **2.7** The Mole and Chemical Formulas *61*
  - Concept Summary *64*
  - Key Terms and Concepts *65*
  - Exercises *65*
  - Additional Exercises *68*
  - Chemistry for Thought *68*
  - **Environmental Career Focus** *46*
  - **HEALTH CONNECTIONS 2.1** Uprooting Herbal Myths *53*
  - **HEALTH CONNECTIONS 2.2** Take Care of Your Bones *54*
  - **STUDY TOOLS 2.1** Help with Mole Calculations *63*
  - **Environmental Career Description** *64*

Chapter 3

Electronic Structure and the Periodic Law 70

- **3.1** The Periodic Law and Table 71
- **3.2** Electronic Arrangements in Atoms 73
- **3.3** The Shell Model and Chemical Properties *76*
- **3.4** Electronic Configurations 78
- **3.5** Another Look at the Periodic Table *82*
- **3.6** Property Trends within the Periodic Table *86*
  - Concept Summary *91*
  - Key Terms and Concepts *92*
  - Exercises *92*
  - Additional Exercises *95*
  - Chemistry for Thought *95*
  - **Health Career Focus** *70*
  - **HEALTH CONNECTIONS 3.1** Watch the Salt *74*
  - **STUDY TOOLS 3.1** The Convention Hotels Analogy *81*
  - **HEALTH CONNECTIONS 3.2** Zinc for Colds? *85*
  - **Health Career Description** *91*

Chapter 4

Forces between Particles 96

- **4.1** Noble Gas Configurations *97*
- **4.2** Ionic Bonding *99*
- **4.3** Ionic Compounds *101*
- **4.4** Naming Binary Ionic Compounds *104*
- **4.5** The Smallest Unit of Ionic Compounds *106*

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

4.6 Covalent Bonding *107*
4.7 Polyatomic Ions *111*
4.8 Shapes of Molecules and Polyatomic Ions *114*
4.9 The Polarity of Covalent Molecules *118*
4.10 More about Naming Compounds *122*
4.11 Other Interparticle Forces *125*
Concept Summary *130*
Key Terms and Concepts *131*
Exercises *132*
Additional Exercises *136*
Chemistry for Thought *136*
Health Career Focus *96*
HEALTH CONNECTIONS 4.1 Consider the Mediterranean Diet *103*
HEALTH CONNECTIONS 4.2 Are All Iron Preparations Created Equal? *119*
STUDY TOOLS 4.1 Help with Polar and Nonpolar Molecules *123*
ENVIRONMENTAL CONNECTIONS 4.1 Ozone: Good Up High, Bad Nearby *127*
Health Career Description *130*

Chapter 5

Chemical Reactions 138

5.1 Chemical Equations *139*
5.2 Types of Reactions *141*
5.3 Redox Reactions *141*
5.4 Decomposition Reactions *145*
5.5 Combination Reactions *146*
5.6 Replacement Reactions *146*
5.7 Ionic Equations *148*
5.8 Energy and Reactions *150*
5.9 The Mole and Chemical Equations *150*
5.10 The Limiting Reactant *153*
5.11 Reaction Yields *155*
Concept Summary *157*
Key Terms and Concepts *158*
Key Equations *158*
Exercises *159*
Additional Exercises *163*
Chemistry for Thought *163*
Health Career Focus *138*
HEALTH CONNECTIONS 5.1 Add Color to Your Diet *150*
HEALTH CONNECTIONS 5.2 Teeth Whitening *152*
STUDY TOOLS 5.1 Help with Oxidation Numbers *156*
Health Career Description *157*

Chapter 6

The States of Matter 164

6.1 Observed Properties of Matter *166*
6.2 The Kinetic Molecular Theory of Matter *168*
6.3 The Solid State *169*
6.4 The Liquid State *170*
6.5 The Gaseous State *170*
6.6 The Gas Laws *171*
6.7 Pressure, Temperature, and Volume Relationships *174*
6.8 The Ideal Gas Law *178*
6.9 Dalton's Law *180*
6.10 Graham's Law *181*
6.11 Changes in State *182*
6.12 Evaporation and Vapor Pressure *183*
6.13 Boiling and the Boiling Point *184*
6.14 Sublimation and Melting *185*
6.15 Energy and the States of Matter *186*
Concept Summary *190*
Key Terms and Concepts *192*
Key Equations *192*
Exercises *193*
Additional Exercises *197*
Chemistry for Thought *197*
Environmental Career Focus *164*
HEALTH CONNECTIONS 6.1 Get an Accurate Blood Pressure Reading *174*
HEALTH CONNECTIONS 6.2 Therapeutic Uses of Oxygen Gas *187*
STUDY TOOLS 6.1 Which Gas Law to Use *189*
Environmental Career Description *190*

Chapter 7

Solutions and Colloids 198

7.1 Physical States of Solutions *199*
7.2 Solubility *200*
7.3 The Solution Process *204*
7.4 Solution Concentrations *208*
7.5 Solution Preparation *212*
7.6 Solution Stoichiometry *216*
7.7 Solution Properties *218*
7.8 Colloids *223*
7.9 Dialysis *226*
Concept Summary *228*

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Key Terms and Concepts *229*
Key Equations *229*
Exercises *230*
Additional Exercises *234*
Chemistry for Thought *235*
Health Career Focus *198*
HEALTH CONNECTIONS 7.1 Stay Hydrated *210*
STUDY TOOLS 7.1 Getting Started with Molarity Calculations *210*
HEALTH CONNECTIONS 7.2 Juices and Sports Drinks *225*
ENVIRONMENTAL CONNECTIONS 7.1 CO_2 Emissions: A Blanket Around the Earth *227*
Health Career Description *227*

Chapter 8

Reaction Rates and Equilibrium 236

8.1 Spontaneous and Nonspontaneous Processes *237*
8.2 Reaction Rates *239*
8.3 Molecular Collisions *240*
8.4 Energy Diagrams *242*
8.5 Factors That Influence Reaction Rates *243*
8.6 Chemical Equilibrium *246*
8.7 The Position of Equilibrium *247*
8.8 Factors That Influence Equilibrium Position *250*
Concept Summary *253*
Key Terms and Concepts *253*
Key Equations *254*
Exercises *254*
Additional Exercises *258*
Chemistry for Thought *258*
Health Career Focus *236*
HEALTH CONNECTIONS 8.1 Energy Drinks *241*
HEALTH CONNECTIONS 8.2 Use Your Phone to Help You Stay Healthy *246*
STUDY TOOLS 8.1 Le Châtelier's Principle in Everyday Life *252*
Health Career Description *252*

Chapter 9

Acids, Bases, and Salts 260

9.1 The Arrhenius Theory *261*
9.2 The Brønsted Theory *261*
9.3 Naming Acids *263*
9.4 The Self-Ionization of Water *265*
9.5 The pH Concept *267*
9.6 Properties of Acids *271*
9.7 Properties of Bases *275*
9.8 Salts *276*
9.9 The Strengths of Acids and Bases *281*
9.10 Analyzing Acids and Bases *285*
9.11 Titration Calculations *287*
9.12 Hydrolysis Reactions of Salts *288*
9.13 Buffers *289*
Concept Summary *293*
Key Terms and Concepts *294*
Key Equations *294*
Exercises *295*
Additional Exercises *302*
Chemistry for Thought *302*
Health Career Focus *260*
ENVIRONMENTAL CONNECTIONS 9.1 Carbon Dioxide in the Oceans *263*
STUDY TOOLS 9.1 Writing Reactions of Acids *276*
HEALTH CONNECTIONS 9.1 Heartburn Alert *284*
Health Career Description *292*

Chapter 10

Radioactivity and Nuclear Processes 304

10.1 Radioactive Nuclei *305*
10.2 Equations for Nuclear Reactions *306*
10.3 Isotope Half-Life *309*
10.4 The Health Effects of Radiation *311*
10.5 Measurement Units for Radiation *313*
10.6 Medical Uses of Radioisotopes *315*
10.7 Nonmedical Uses of Radioisotopes *317*
10.8 Induced Nuclear Reactions *318*
10.9 Nuclear Energy *321*
Concept Summary *325*
Key Terms and Concepts *326*
Key Equations *327*
Exercises *327*
Additional Exercises *329*
Chemistry for Thought *329*
Health Career Focus *304*
HEALTH CONNECTIONS 10.1 Diagnostic Radiation *314*

HEALTH CONNECTIONS 10.2 Check the Radon Level in Your Home *318*
Health Career Description *325*

Chapter 11

Organic Compounds: Alkanes 330

11.1 Carbon: The Element of Organic Compounds *331*
11.2 Organic and Inorganic Compounds Compared *332*
11.3 Bonding Characteristics and Isomerism *334*
11.4 Functional Groups: The Organization of Organic Chemistry *336*
11.5 Alkane Structures *339*
11.6 Conformations of Alkanes *343*
11.7 Alkane Nomenclature *345*
11.8 Cycloalkanes *352*
11.9 The Shape of Cycloalkanes *354*
11.10 Physical Properties of Alkanes *357*
11.11 Alkane Reactions *359*
Concept Summary *362*
Key Terms and Concepts *363*
Key Equations *363*
Exercises *363*
Additional Exercises *371*
Chemistry for Thought *371*
Environmental Career Focus *330*
STUDY TOOLS 11.1 Changing Gears for Organic Chemistry *334*
HEALTH CONNECTIONS 11.1 Is Organic Food Worth the Price? *340*
HEALTH CONNECTIONS 11.2 Take Care of Dry Skin *357*
ENVIRONMENTAL CONNECTIONS 11.1 Reducing Your Carbon Footprint *359*
Environmental Career Description *361*

Chapter 12

Unsaturated Hydrocarbons 372

12.1 The Nomenclature of Alkenes *374*
12.2 The Geometry of Alkenes *376*
12.3 Properties of Alkenes *380*
12.4 Addition Polymers *386*
12.5 Alkynes *390*
12.6 Aromatic Compounds and the Benzene Structure *391*
12.7 The Nomenclature of Benzene Derivatives *393*
12.8 Properties and Uses of Aromatic Compounds *396*
Concept Summary *398*
Key Terms and Concepts *399*
Key Equations *399*
Exercises *400*
Additional Exercises *406*
Chemistry for Thought *406*
Health Career Focus *372*
HEALTH CONNECTIONS 12.1 Three-Dimensional Printers *378*
STUDY TOOLS 12.1 Keeping a Reaction Card File *385*
STUDY TOOLS 12.2 A Reaction Map for Alkenes *388*
HEALTH CONNECTIONS 12.2 Think before Getting Brown *395*
Health Career Description *398*

Chapter 13

Alcohols, Phenols, and Ethers 408

13.1 The Nomenclature of Alcohols and Phenols *410*
13.2 Classification of Alcohols *412*
13.3 Physical Properties of Alcohols *413*
13.4 Reactions of Alcohols *415*
13.5 Important Alcohols *422*
13.6 Characteristics and Uses of Phenols *425*
13.7 Ethers *428*
13.8 Properties of Ethers *429*
13.9 Thiols *430*
13.10 Polyfunctional Compounds *433*
Concept Summary *435*
Key Terms and Concepts *436*
Key Reactions *436*
Exercises *437*
Additional Exercises *444*
Chemistry for Thought *444*
Health Career Focus *408*
STUDY TOOLS 13.1 A Reaction Map for Alcohols *423*
HEALTH CONNECTIONS 13.1 Alcohol and Antidepressants Don't Mix *424*
HEALTH CONNECTIONS 13.2 Take Advantage of Hand Sanitizers *427*
HEALTH CONNECTIONS 13.3 General Anesthetics *430*
Health Career Description *434*

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Chapter 14

Aldehydes and Ketones 446

14.1 The Nomenclature of Aldehydes and Ketones *447*
14.2 Physical Properties *450*
14.3 Chemical Properties *452*
14.4 Important Aldehydes and Ketones *464*
Concept Summary *466*
Key Terms and Concepts *467*
Key Equations *467*
Exercises *468*
Additional Exercises *476*
Chemistry for Thought *476*
Health Career Focus *446*
HEALTH CONNECTIONS 14.1 Faking a Tan *451*
STUDY TOOLS 14.1 A Reaction Map for Aldehydes and Ketones *460*
HEALTH CONNECTIONS 14.2 Vanilloids: Hot Relief from Pain *463*
Health Career Description *465*

Chapter 15

Carboxylic Acids and Esters 478

15.1 The Nomenclature of Carboxylic Acids *479*
15.2 Physical Properties of Carboxylic Acids *481*
15.3 The Acidity of Carboxylic Acids *483*
15.4 Salts of Carboxylic Acids *485*
15.5 Carboxylic Esters *487*
15.6 The Nomenclature of Esters *492*
15.7 Reactions of Esters *493*
15.8 Esters of Inorganic Acids *497*
Concept Summary *499*
Key Terms and Concepts *500*
Key Equations *500*
Exercises *501*
Additional Exercises *507*
Chemistry for Thought *507*
Health Career Focus *478*
ENVIRONMENTAL CONNECTIONS 15.1 Plastics: Cleanup Time *489*
HEALTH CONNECTIONS 15.1 Consider Low-Dose Aspirin *495*
STUDY TOOLS 15.1 A Reaction Map for Carboxylic Acids *496*
HEALTH CONNECTIONS 15.2 Nitroglycerin in Dynamite and in Medicine *498*
Health Career Description *499*

Chapter 16

Amines and Amides 510

16.1 Classification of Amines *511*
16.2 The Nomenclature of Amines *512*
16.3 Physical Properties of Amines *514*
16.4 Chemical Properties of Amines *515*
16.5 Amines as Neurotransmitters *522*
16.6 Other Biologically Important Amines *525*
16.7 The Nomenclature of Amides *528*
16.8 Physical Properties of Amides *530*
16.9 Chemical Properties of Amides *532*
Concept Summary *535*
Key Terms and Concepts *536*
Key Equations *536*
Exercises *536*
Additional Exercises *543*
Chemistry for Thought *543*
Health Career Focus *510*
HEALTH CONNECTIONS 16.1 Aspirin Substitutes *522*
STUDY TOOLS 16.1 A Reaction Map for Amines *525*
HEALTH CONNECTIONS 16.2 Try a Little Chocolate *528*
Health Career Description *534*

Chapter 17

Carbohydrates 546

17.1 Classes of Carbohydrates *547*
17.2 The Stereochemistry of Carbohydrates *548*
17.3 Fischer Projections *552*
17.4 Monosaccharides *556*
17.5 Properties of Monosaccharides *557*
17.6 Important Monosaccharides *563*
17.7 Disaccharides *564*
17.8 Polysaccharides *568*
Concept Summary *572*
Key Terms and Concepts *573*
Key Equations *573*
Exercises *574*
Additional Exercises *579*
Chemistry for Thought *579*

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Health Career Focus 546
HEALTH CONNECTIONS 17.1 Sugar-Free Foods and Diabetes 561
STUDY TOOLS 17.1 Biomolecules: A New Focus 565
HEALTH CONNECTIONS 17.2 Put Fiber into Snacks and Meals 571
Health Career Description 572

Chapter 18
Lipids 582
18.1 Classification of Lipids 583
18.2 Fatty Acids 584
18.3 The Structure of Fats and Oils 588
18.4 Chemical Properties of Fats and Oils 589
18.5 Waxes 594
18.6 Phosphoglycerides 594
18.7 Sphingolipids 597
18.8 Biological Membranes 600
18.9 Steroids 602
18.10 Steroid Hormones 604
18.11 Prostaglandins 606
Concept Summary 608
Key Terms and Concepts 609
Key Equations 609
Exercises 610
Additional Exercises 613
Chemistry for Thought 613
Health Career Focus 582
STUDY TOOLS 18.1 A Reaction Map for Triglycerides 594
HEALTH CONNECTIONS 18.1 Consider Olive Oil 606
Health Career Description 607

Chapter 19
Proteins 614
19.1 The Amino Acids 615
19.2 Zwitterions 618
19.3 Reactions of Amino Acids 620
19.4 Important Peptides 624
19.5 Characteristics of Proteins 625
19.6 The Primary Structure of Proteins 628
19.7 The Secondary Structure of Proteins 629
19.8 The Tertiary Structure of Proteins 632
19.9 The Quaternary Structure of Proteins 634
19.10 Protein Hydrolysis and Denaturation 636
Concept Summary 638
Key Terms and Concepts 639
Key Equations 640
Exercises 641
Additional Exercises 644
Chemistry for Thought 644
Health Career Focus 614
HEALTH CONNECTIONS 19.1 Higher-Protein Diet 621
HEALTH CONNECTIONS 19.2 A Milk Primer 632
STUDY TOOLS 19.1 Visualizing Protein Structure 636
Health Career Description 638

Chapter 20
Enzymes 646
20.1 General Characteristics of Enzymes 647
20.2 Enzyme Nomenclature and Classification 648
20.3 Enzyme Cofactors 650
20.4 The Mechanism of Enzyme Action 651
20.5 Enzyme Activity 652
20.6 Factors Affecting Enzyme Activity 653
20.7 Enzyme Inhibition 655
20.8 The Regulation of Enzyme Activity 660
20.9 Medical Application of Enzymes 663
Concept Summary 665
Key Terms and Concepts 666
Key Equations 666
Exercises 666
Additional Exercises 670
Chemistry for Thought 670
Health Career Focus 646
HEALTH CONNECTIONS 20.1 Cut Back on Processed Meat 650
HEALTH CONNECTIONS 20.2 No Milk, Please 658
STUDY TOOLS 20.1 A Summary Chart of Enzyme Inhibitors 662
Health Career Description 665

Chapter 21
Nucleic Acids and Protein Synthesis 672
21.1 Components of Nucleic Acids 673
21.2 The Structure of DNA 676
21.3 DNA Replication 680

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

21.4 Ribonucleic Acid (RNA) *684*
21.5 The Flow of Genetic Information *687*
21.6 Transcription: RNA Synthesis *688*
21.7 The Genetic Code *690*
21.8 Translation and Protein Synthesis *693*
21.9 Mutations *695*
21.10 Recombinant DNA *696*
Concept Summary *700*
Key Terms and Concepts *701*
Exercises *701*
Additional Exercises *704*
Chemistry for Thought *705*
Environmental Career Focus *672*
HEALTH CONNECTIONS 21.1 Is There a DNA Checkup in Your Future? *690*
STUDY TOOLS 21.1 Remembering Key Words *692*
HEALTH CONNECTIONS 21.2 Gene Editing and Your Health *697*
Environmental Career Description *699*

Chapter 22

Nutrition and Energy for Life 706

22.1 Nutritional Requirements *707*
22.2 The Macronutrients *709*
22.3 Micronutrients I: Vitamins *712*
22.4 Micronutrients II: Minerals *714*
22.5 The Flow of Energy in the Biosphere *716*
22.6 Metabolism and an Overview of Energy Production *718*
22.7 ATP: The Primary Energy Carrier *720*
22.8 Important Coenzymes in the Common Catabolic Pathway *724*
Concept Summary *730*
Key Terms and Concepts *731*
Key Equations *731*
Exercises *732*
Additional Exercises *735*
Chemistry for Thought *735*
Health Career Focus *706*
HEALTH CONNECTIONS 22.1 Select a Heart-Healthful Diet *714*
STUDY TOOLS 22.1 Bioprocesses *722*
HEALTH CONNECTIONS 22.2 Fiber Supplements? *728*
Health Career Description *730*

Chapter 23

Carbohydrate Metabolism 736

23.1 The Digestion of Carbohydrates *737*
23.2 Blood Glucose *737*
23.3 Glycolysis *738*
23.4 The Fates of Pyruvate *741*
23.5 The Citric Acid Cycle *743*
23.6 The Electron Transport Chain *746*
23.7 Oxidative Phosphorylation *747*
23.8 The Complete Oxidation of Glucose *749*
23.9 Glycogen Metabolism *751*
23.10 Gluconeogenesis *753*
23.11 The Hormonal Control of Carbohydrate Metabolism *754*
Concept Summary *755*
Key Terms and Concepts *757*
Key Equations *757*
Exercises *758*
Additional Exercises *761*
Chemistry for Thought *761*
Health Career Focus *736*
HEALTH CONNECTIONS 23.1 How Can We Avoid Energy Crashes? *740*
HEALTH CONNECTIONS 23.2 Lactate Accumulation *745*
STUDY TOOLS 23.1 Key Numbers for ATP Calculations *752*
Health Career Description *755*

Chapter 24

Lipid and Amino Acid Metabolism 762

24.1 Blood Lipids *763*
24.2 Fat Mobilization *766*
24.3 Glycerol Metabolism *767*
24.4 The Oxidation of Fatty Acids *767*
24.5 The Energy from Fatty Acids *770*
24.6 Ketone Bodies *771*
24.7 Fatty Acid Synthesis *773*
24.8 Amino Acid Metabolism *774*
24.9 Amino Acid Catabolism: The Fate of the Nitrogen Atoms *776*
24.10 Amino Acid Catabolism: The Fate of the Carbon Skeleton *780*

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

24.11 Amino Acid Biosynthesis *783*
Concept Summary *785*
Key Terms and Concepts *786*
Key Equations *786*
Exercises *787*
Additional Exercises *789*
Chemistry for Thought *790*
Health Career Focus *762*
HEALTH CONNECTIONS 24.1 Are Certain Foods Better for the Brain? *765*
STUDY TOOLS 24.1 Key Numbers for ATP Calculations *773*
HEALTH CONNECTIONS 24.2 Phenylketonuria (PKU) *781*
HEALTH CONNECTIONS 24.3 Phenylalanine and Diet Foods *782*
Health Career Description *784*

Chapter 25

Body Fluids 792

25.1 A Comparison of Body Fluids *793*
25.2 Oxygen and Carbon Dioxide Transport *794*
25.3 Chemical Transport to the Cells *797*
25.4 The Constituents of Urine *798*
25.5 Fluid and Electrolyte Balance *799*
25.6 Acid–Base Balance *801*
25.7 Buffer Control of Blood pH *801*
25.8 Respiratory Control of Blood pH *802*
25.9 Urinary Control of Blood pH *802*
25.10 Acidosis and Alkalosis *803*
Concept Summary *806*
Key Terms and Concepts *808*
Key Equations *808*
Exercises *808*
Additional Exercises *810*
Chemistry for Thought *810*
Health Career Focus *792*
HEALTH CONNECTIONS 25.1 Pulse Oximetry *800*
Health Career Description *806*

Appendix A The International System of Measurements *A-1*
Appendix B Answers to Even-Numbered End-of-Chapter Exercises *B-1*
Appendix C Solutions to Learning Checks *C-1*
Glossary *G-1*
Index *I-1*

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Preface

The Image of Chemistry

We, as authors, are pleased that the acceptance of the previous nine editions of this textbook by students and their teachers has made it possible to publish this tenth edition. In the earlier editions, we expressed our concern about the negative image of chemistry held by many of our students, and their genuine fear of working with chemicals in the laboratory. Unfortunately, this negative image not only persists, but seems to be intensifying. Reports in the media related to chemicals or to chemistry continue to be primarily negative, and in many cases seem to be designed to increase the fear and concern of the general public. With this edition, we continue to hope that those who use this book will gain a more positive understanding and appreciation of the important contributions that chemistry makes in their lives.

Theme and Organization

This edition continues the theme of the positive and useful contributions made by chemistry in our world.

This text is designed to be used in either a two-semester or three-quarter course of study that provides an introduction to general chemistry, organic chemistry, and biochemistry. Most students who take such courses are majoring in nursing, other health professions, or the life sciences, and consider biochemistry to be the most relevant part of the course of study. However, an understanding of biochemistry depends upon a sound background in organic chemistry, which in turn depends upon a good foundation in general chemistry. We have attempted to present the general and organic chemistry in sufficient depth and breadth to make the biochemistry understandable.

The decisions about what to include and what to omit from the text were based on our combined 75-plus years of teaching, input from numerous reviewers and adopters, and our philosophy that a textbook functions as a personal tutor to each student. In the role of a personal tutor, a text must be more than just a collection of facts, data, and exercises. It should also help students relate to the material they are studying, carefully guide them through more difficult material, provide them with interesting and relevant examples of chemistry in their lives, and become a reference and a resource that they can use in other courses or their professions.

New to This Edition

In this tenth edition of the text, we have some exciting new features, including Career Focus boxes written by Monica Linford and Health Connections. We have also retained features that received a positive reception from our own students, the students of other adopters, other teachers, and reviewers. Over 133 figures and 170 examples have been added to the chapters. Many of these new figures and examples are health-related. Moreover, 559 end-of-chapter exercises have been added.

Also new to this edition are many new photographs and updated art to further enhance student comprehension of key concepts, processes, and test preparation.

Revision Summary of Tenth Edition

Chapter 1

- New Career Focus
- New Career Description
- 8 new or revised figures
- 11 new or revised Examples
- New photography
- 22 new Exercises

Chapter 2

- New Career Focus
- New Career Description
- 5 new or revised Examples
- 7 new or revised figures
- New photography
- 10 new Exercises

Chapter 3

- New Career Focus
- New Career Description
- 4 new or revised Examples
- 4 new or revised figures
- New photography
- 10 revised Exercises

Chapter 4

- New Career Focus
- New Career Description
- 10 new or revised Examples
- 6 new or revised figures
- New photography
- 12 new or revised Exercises

Chapter 5

- New Career Focus
- New Career Description
- 4 new or revised figures
- 6 new or revised Examples
- New photography
- 11 new or revised Exercises

Chapter 6

- New Career Focus
- New Career Description
- 8 new or revised Examples
- 8 new or revised figures
- New photography
- 22 new Exercises

Chapter 7

- New Career Focus
- New Career Description
- 8 new or revised figures
- New photography
- 7 new or revised Examples
- 9 new Exercises

Chapter 8

- New Career Focus
- New Career Description
- 3 new or revised Examples
- Several revised figures
- New photography

Chapter 9

- New Career Focus
- New Career Description
- 7 new or revised Examples
- 12 new or revised figures
- New photography
- 19 new Exercises

Chapter 10

- New Career Focus
- New Career Description
- 3 new or revised Examples
- 7 new or revised figures
- New photography
- 5 new Exercises

Chapter 11

- New Career Focus
- New Career Description
- 9 new or revised Examples
- 9 new or revised figures
- New photography
- 30 new Exercises

Chapter 12

- New Career Focus
- New Career Description
- 7 new or revised Examples
- 7 new or revised figures
- New photography
- 29 new Exercises

Chapter 13

- New Career Focus
- New Career Description
- 12 new or revised Examples
- 6 new or revised figures
- New photography
- 33 new Exercises

Chapter 14

- New Career Focus
- New Career Description
- 6 new or revised Examples
- New photography
- 36 new Exercises

Chapter 15

- New Career Focus
- New Career Description
- 4 new or revised Examples
- 5 new or revised figures
- New photography
- 31 new Exercises

Chapter 16

- New Career Focus
- New Career Description
- 11 new or revised Examples
- 5 new or revised figures
- New photography
- 31 new Exercises

Chapter 17

- New Career Focus
- New Career Description
- 7 new or revised Examples
- 4 new or revised figures
- New photography
- 30 new Exercises

Chapter 18

- New Career Focus
- New Career Description
- 10 new or revised Examples
- 7 new or revised figures
- New photography
- 30 new Exercises

Chapter 19

- New Career Focus
- New Career Description
- 7 new or revised Examples
- 5 new or revised figures
- New photography
- 30 new Exercises

Chapter 20

- New Career Focus
- New Career Description
- 5 new or revised Examples
- 6 new or revised figures
- New photography
- 30 new Exercises

Chapter 21

- New Career Focus
- New Career Description
- 5 new or revised Examples
- New photography
- 30 new Exercises

Chapter 22

- New Career Focus
- New Career Description
- 6 new or revised Examples
- Figure revised to show a current food label
- New photography
- 30 new Exercises

Chapter 23

- New Career Focus
- New Career Description
- 5 new or revised Examples
- New photography
- 30 new Exercises

Chapter 24

- New Career Focus
- New Career Description
- 8 new or revised Examples
- New photography
- 30 new Exercises

Chapter 25

- New Career Focus
- New Career Description
- 4 new or revised Examples
- New photography
- 30 new Exercises

Features

Each chapter has features especially designed to help students study effectively, as well as organize, understand, and enjoy the material in the course.

Career Focus. These features introduce the diverse fields of health care. The purpose of the career focus features is to stimulate inquiry; for that reason, we've placed them at the beginning of each chapter of the book. Vocabulary and scenarios may be unfamiliar to you who are studying these course materials, but our intent is to raise interest and pique your curiosity. A career description can be found at the end of each chapter before the Concept Summary.

Health Career Focus

STERILE PROCESSING TECHNICIAN

"Without us, nothing happens in this hospital. We're essential to every treatment, procedure, and surgery that occurs in this facility."

"Here's my locker where I change into my PPE, or personal protective equipment—just as if I were dressing for surgery—including foot coverings and a face shield."

"There, behind that window, we receive trays of used surgical equipment. We meticulously wash the blood, bone, and tissue off and get them ready for steam-pressure sterilization. This job isn't for the squeamish."

"One of the most important parts of my job is actually counting the instruments, making sure each item returns from surgery and is recorded carefully in the database. I also monitor equipment for

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Chapter Outlines and Learning Objectives. At the beginning of each chapter, a list of learning objectives provides students with a convenient overview of what they should gain by studying the chapter. In order to help students navigate through each chapter and focus on key concepts, these objectives are repeated at the beginning of the section in which the applicable information is discussed. The objectives are referred to again in question format the concept summary at the end of each chapter. Thus, students begin each chapter with a set of objectives and end with an indication of how well they satisfied the objectives.

Key Terms. Identified within the text by the use of bold type, key terms are defined in the margin near the place where they are introduced. Students reviewing a chapter can quickly identify the important concepts on each page with this marginal glossary. A full glossary of key terms and concepts appears at the end of the text.

Environmental Connections. These boxed features contain current chemistry-related environmental issues such as “Ozone: Good Up High, Bad Nearby” and “CO_2 Emissions: A Blanket around the Earth.”

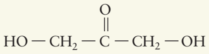
Health Connections. These boxed features contain current chemistry-related health issues such as “Add Color to Your Diet,” and suggestions for maintaining good health such as “Consider the Mediterranean Diet,” “Cut Back on Processed Meat,” and “Try a Little Chocolate.”

HEALTH CONNECTIONS **14.1**

Faking a Tan

Many people believe that a suntan makes one look healthy and attractive. Studies, however, indicate that this perception is far from the truth. According to these studies, sunbathing, especially when sunburn results, ages the skin prematurely and increases the risk of skin cancer. Cosmetic companies have developed a tanning alternative for those not willing to risk using the sun but who want to be “fashionably” tan.

Tanning lotions and creams that chemically darken the skin are now available. The active ingredient in these “bronzers” is dihydroxyacetone (DHA), a colorless compound classified by the Food and Drug Administration as a safe skin dye.



$$HO-CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-CH_2-OH$$

dihydroxyacetone (DHA)

Within several hours after application, DHA produces a brown skin color by reacting with the outer layer of the skin, which consists of dead cells. Only the dead cells react with DHA, so the color gradually fades as the dead cells slough off and are replaced. This process generally leads to the fading of chemical tans within a few weeks. Another problem with chemical tans is uneven skin color. Areas of skin such as elbows and knees, which contain a thicker layer of dead cells, may absorb and react with more tanning lotion and become darker than other areas.

Perhaps the greatest problem with chemical tans is the false sense of security they might give. Some people with chemical tans think it is safe to go into the sun and get a deeper tan. This isn’t true. Sunlight presents the same hazards to chemically tanned skin that it does to untanned skin.

Neutrogena
Sunless Tanning
Coppertone
Sunless
Banana Boat
Sunless
Deep Dark Blend
Banana Boat
SUNLESS
Tanning Spray

© Maren Slabaugh

Some DHA-containing products.

Examples. To reinforce students in their problem-solving skill development, complete step-by-step solutions for numerous examples are included.

Learning Checks. Short self-check exercises follow examples and discussions of key or difficult concepts. A complete set of solutions is included in Appendix C. These allow students to measure immediately their understanding and progress.

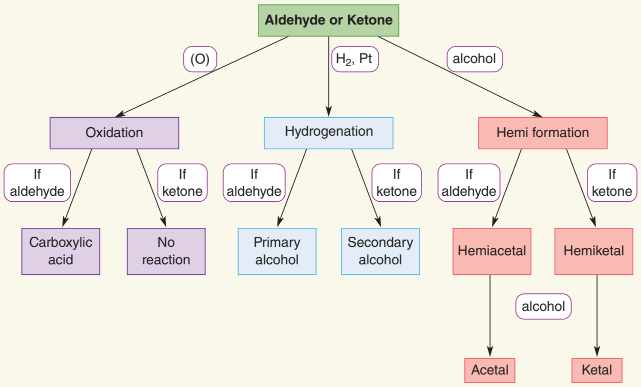
Study Tools. Most chapters contain a *Study Tools* feature in which a challenging topic, skill, or concept of the chapter is addressed. Study suggestions, analogies, and approaches are provided to help students master these ideas.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STUDY TOOLS 14.1

A Reaction Map for Aldehydes and Ketones

This reaction map is designed to help you master organic reactions. Whenever you are trying to complete an organic reaction, use these two basic steps: (1) Identify the functional group that is to react, and (2) Identify the reagent that is to react with the functional group. If the reacting functional group is an aldehyde or a ketone, find the reagent in the summary diagram, and use the diagram to predict the correct products.



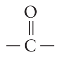
Concept Summary. Located at the end of each chapter, this feature provides a concise review of the concepts and challenges students to check their achievement of the learning objectives related to the concepts.

Concept Summary

14.1 The Nomenclature of Aldehydes and Ketones

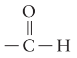
Learning Objective: Can you recognize the carbonyl group in compounds and classify the compounds as aldehydes or ketones? Can you assign IUPAC name to aldehydes and ketones?

- The functional groups characteristic of aldehydes and ketones are very similar.



$$-\overset{\overset{\Large O}{\|}}{C}-$$

- They both contain a carbonyl group.
- Aldehydes have a hydrogen attached to the carbonyl carbon.



$$-\overset{\overset{\Large O}{\|}}{C}-H$$

- The polarity of the carbonyl group and the fact that aldehydes and ketones can form hydrogen bonds with water explain why the low-molecular-weight compounds of these organic classes are water-soluble.

14.3 Chemical Properties

Learning Objective: Can you write key reactions for aldehydes and ketones?

- Aldehydes are prepared by the oxidation of primary alcohols.
- Ketones are prepared by the oxidation of secondary alcohols.
- Aldehydes can be further oxidized to carboxylic acids, but ketones resist oxidation.
- Thus, aldehydes are oxidized by Tollens' reagent (Ag^+) and Benedict's solution (Cu^{2+}), whereas ketones are not.
- A characteristic reaction of both aldehydes and ketones is the addition of hydrogen to the carbonyl double bond to form alcohols.

Key Terms and Concepts. These are listed at the end of each chapter for easy review, with a reference to the chapter section in which they are presented.

Key Equations. This feature provides a useful summary of general equations and reactions from the chapter. This feature is particularly helpful to students in the organic chemistry chapters.

Exercises. Nearly 2200 end-of-chapter exercises are arranged by section. Approximately half of the exercises are answered in the back of the text. Solutions and answers to all exercises are provided in the Instructor's Manual. We have included a significant number of clinical and other familiar applications of chemistry in the exercises.

Chemistry for Thought. Included at the end of each chapter are special questions designed to encourage students to expand their reasoning skills. Some of these exercises are based on photographs found in the chapter, while others emphasize clinical or other useful applications of chemistry.

Possible Course Outlines

This text may be used effectively in either a two-semester or three-quarter course of study:

First semester: Chapters 1–13 (general chemistry and three chapters of organic chemistry)

Second semester: Chapters 14–25 (organic chemistry and biochemistry)

First semester: Chapters 1–10 (general chemistry)

Second semester: Chapters 11–21 (organic chemistry and some biochemistry)

First quarter: Chapters 1–10 (general chemistry)

Second quarter: Chapters 11–18 (organic chemistry)

Third quarter: Chapters 19–25 (biochemistry)

Supporting Materials

Additional instructor resources for this product are available online. Instructor assets include an Instructor's Manual including solutions to exercises, an Educator's Guide describing digital homework assets, a Transition Guide (9th to 10th edition), PowerPoint® slides, and a Test Bank powered by Cognero®. Sign up or sign in at **www.cengage.com** to search for and access this product and its online resources.

Acknowledgments

We express our sincere appreciation to the following reviewers, who helped us revise many editions:

Hugh Akers
Lamar University–Beaumont

Johanne I. Artman
Del Mar College

Gabriele Backes
Portland Community College

Bruce Banks
University of North Carolina–Greensboro

David Boykin
Georgia State University

Deb Breiter
Rockford College

Lorraine C. Brewer
University of Arkansas

Martin Brock
Eastern Kentucky University

Jonathan T. Brockman
College of DuPage

Kathleen Brunke
Christopher Newport University

Christine Brzezowski
University of Utah

Sybil K. Burgess
University of North Carolina–Wilmington

Sharmaine S. Cady
East Stroudsburg University

Linda J. Chandler
Salt Lake Community College

Tom Chang
Utah State University

Ngee Sing Chong
Middle Tennessee State University

Judith Ciottone
Fitchburg State University

Elizabeth Clizbe
University at Buffalo

Caroline Clower
Clayton State University

Sharon Cruse
Northern Louisiana University

Thomas D. Crute
Augusta College

Jack L. Dalton
Boise State University

Lorraine Deck
University of New Mexico

Kathleen A. Donnelly
Russell Sage College

Jan Fausset
Front Range Community College

Patricia Fish
The College of St. Catherine

Harold Fisher
University of Rhode Island

John W. Francis
Columbus State Community College

Wes Fritz
College of DuPage

Jean Gade
Northern Kentucky University

Galen George
Santa Rosa Junior College

Anita Gnezda
Ball State University

Meldath Govindan
Fitchburg State University

Jane D. Grant
Florida Community College

James K. Hardy
University of Akron

Leland Harris
University of Arizona

Robert H. Harris
University of Nebraska–Lincoln

David C. Hawkinson
University of South Dakota

Jack Hefley
Blinn College

Claudia Hein
Diablo Valley College

John Henderson
Jackson Community College

Mary Herrmann
University of Cincinnati

Arthur R. Hubscher
Brigham Young University–Idaho

Kenneth Hughes
University of Wisconsin–Oshkosh

Jeffrey A. Hurlbut
Metropolitan State College of Denver

Jim Johnson
Sinclair Community College

Richard. F. Jones
Sinclair Community College

Frederick Jury
Collin County Community College

Lidija Kampa
Kean College of New Jersey

Laura Kibler-Herzog
Georgia State University

Margaret G. Kimble
Indiana University–Purdue University Fort Wayne

James F. Kirby
Quinnipiac University

Peter J. Krieger
Palm Beach Community College

Terrie L. Lampe
De Kalb College–Central Campus

Carol Larocque
Cambrian College

Richard Lavallee
Santa Monica College

Donald Linn
Indiana University—Purdue University Fort Wayne

Leslie J. Lovett
Fairmont State College

James Luba
University of Arkansas at Little Rock

Regan Luken
University of South Dakota

Gregory Marks
Carroll University

Matthew Marmorino
Indiana University South Bend

Armin Mayr
El Paso Community College

James McConaghy
Wayne College

Evan McHugh
Pikes Peak Community College

Trudy McKee
Thomas Jefferson University

Melvin Merken
Worcester State College

W. Robert Midden
Bowling Green State University

Pamela S. Mork
Concordia College

Phillip E. Morris, Jr.
University of Alabama–Birmingham

Robert N. Nelson
Georgia Southern University

Marie Nguyen
Highline Community College

Elva Mae Nicholson
Eastern Michigan University

H. Clyde Odom
Charleston Southern University

Howard K. Ono
California State University–Fresno

Jeff Owens
Highline Community College

Dwight Patterson
Middle Tennessee State University

James A. Petrich
San Antonio College

Patrick Pierce
California State University Long Beach

Thomas G. Richmond
University of Utah

Kira Rose
University of Central Oklahoma

James Schreck
University of Northern Colorado

William Scovell
Bowling Green State University

Jean M. Shankweiler
El Camino Community College

Francis X. Smith
King's College

J. Donald Smith
University of Massachusetts–Dartmouth

Malcolm P. Stevens
University of Hartford

Eric R. Taylor
University of Southwestern Louisiana

Krista Thomas
Johnson County Community College

Linda Thomas-Glover
Guilford Technical Community College

James A. Thomson
University of Waterloo

Mary Lee Trawick
Baylor University

Katherin Vafeades
University of Texas–San Antonio

Peter van der Geer
San Diego State University

John Vincent
University of Alabama

Anne Vonderheide
University of Cincinnati

Scott White
Southern Arkansas University

Cary Willard
Grossmont College

Don Williams
Hope College

Les Wynston
California State University–Long Beach

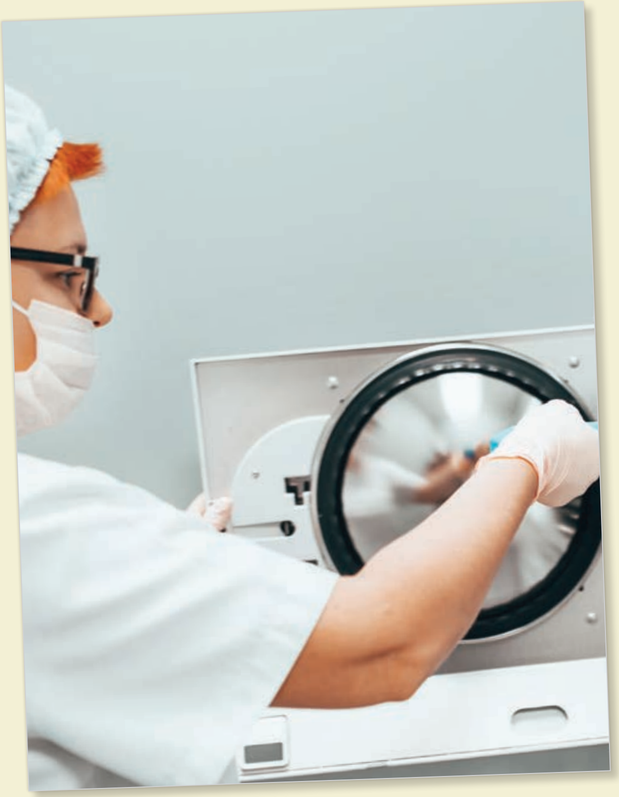
Jean Yockey
University of South Dakota

We also give special thanks to the staff of Cengage Learning including Helene Alfaro and Roxanne Wang, Product Managers, and Susan Pashos, Learning Designer, who guided and encouraged us in the preparation of this tenth edition. We would also like to thank Brendan Killion and Meaghan Ford, Content Managers; Dakin Sharum, Subject Matter Expert; Beth McCracken, Digital Delivery Lead, Ivan Corriher, OWLv2 Program Manager; and Andrew Stock, Marketing Manager. Timothy Cali's work in marketing is also sincerely appreciated. These and other people were essential to the team and contributed greatly to the success of the project. We are grateful for the superb work of Charu Verma of MPS Limited for her outstanding coordination of production and accuracy checking, and to Kelli Besse, IP Project Manager, for coordinating the many new excellent photos. We are especially pleased with the new Career Focus/Career Description feature and wish to thank Monica Linford for her excellent work. We appreciate the significant help of four associates: Mary Ann Francis, who did an excellent job of preparing and submitting the manuscript; Wayne Aprill, who helped write new exercises; and Tracy Covey and Brandon Burnett, who helped revise organic and biochemistry chapters.

Finally, we extend our love and heartfelt thanks to our families for their patience, support, encouragement, and understanding during a project that occupied much of our time and energy.

Spencer L. Seager
Michael R. Slabaugh
Maren S. Hansen

1 Matter, Measurements, and Calculations



VanoVasaio/Shutterstock.com

Health Career Focus

STERILE PROCESSING TECHNICIAN

"Without us, nothing happens in this hospital. We're essential to every treatment, procedure, and surgery that occurs in this facility."

"Here's my locker where I change into my PPE, or personal protective equipment—just as if I were dressing for surgery—including foot coverings and a face shield."

"There, behind that window, we receive trays of used surgical equipment. We meticulously wash the blood, bone, and tissue off and get them ready for steam-pressure sterilization. This job isn't for the squeamish."

"One of the most important parts of my job is actually counting the instruments, making sure each item returns from surgery and is recorded carefully in the database. I also monitor equipment for proper temperatures and settings to ensure we meet protocols."

"This job requires extreme attention to detail. I initial everything I sterilize. My work is traceable to me. Precision is important."

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you complete the study of this chapter, you should be able to:

1. Explain what matter is. **(Section 1.1)**
2. Explain the difference between the terms *physical* and *chemical* as applied to the properties of matter and changes in matter. **(Section 1.2)**
3. Describe matter in terms of the accepted scientific model. **(Section 1.3)**
4. On the basis of observation or information given to you, classify matter into the correct category of each of the following pairs: heterogeneous or homogeneous, solution or pure substance, and element or compound. **(Section 1.4)**
5. Recognize the use of measurement units in everyday activities. **(Section 1.5)**

6. Recognize units of the metric system, and convert measurements done using the metric system into related units. **(Section 1.6)**
7. Express numbers using scientific notation and do calculations with numbers expressed in scientific notation. **(Section 1.7)**
8. Express the results of measurements and calculations using the correct number of significant figures. **(Section 1.8)**
9. Use the factor-unit method to solve numerical problems. **(Section 1.9)**
10. Do calculations involving percentages. **(Section 1.10)**
11. Do calculations involving densities. **(Section 1.11)**

CHEMISTRY is often described as the scientific study of matter. In a way, almost every study is a study of matter, because matter is the substance of everything. However, chemists are especially interested in matter; they study it and attempt to understand it from nearly every possible point of view.

The chemical nature of all matter makes an understanding of chemistry useful and necessary for individuals who are studying in a wide variety of areas, including the health sciences, natural sciences, home economics, education, environmental science, and law enforcement.

Matter comes in many shapes, sizes, and colors that are interesting to look at and describe. Early chemists did little more than describe what they observed, and their chemistry was a descriptive science that was severely limited in scope. It became a much more useful science when chemists began to make quantitative measurements, do calculations, and incorporate the results into their descriptions. Some fundamental ideas about matter are presented in this chapter, along with some ideas about quantitative measurement, the scientific measurement system, and calculations.

1.1 What Is Matter?

Learning Objective 1 Explain what matter is.

Definitions are useful in all areas of knowledge. They provide a common vocabulary for both presentations to students and discussions between professionals. You will be expected to learn a number of definitions as you study chemistry, and the first one is a definition of *matter*. Earlier, we said that matter is the substance of everything. That isn't very scientific, even though we think we know what it means. If you stop reading for a moment and look around, you will see a number of objects that might include people, potted plants, walls, furniture, books, windows, and a TV set or radio. The objects you see have at least two things in common: Each one has mass, and each one occupies space. These two common characteristics provide the basis for the scientific definition of matter. **Matter** is anything that has mass and occupies space. You probably understand what is meant by an object occupying space, especially if you have tried to occupy

matter Anything that has mass and occupies space.

the same space as some other object. The resulting physical bruises leave a lasting mental impression.

You might not understand the meaning of the term *mass* quite as well, but it can also be illustrated "painfully." Imagine walking into a very dimly lit room and being able to just barely see two large objects of equal size on the floor. You know that one is a bowling ball and the other is an inflated plastic ball, but you can't visually identify which is which. However, a hard kick delivered to either object easily allows you to identify each one. The bowling ball resists being moved much more strongly than does the inflated ball. Resistance to movement depends on the amount of matter in an object, and **mass** is an actual measurement of the amount of matter present.

mass A measurement of the amount of matter in an object.

The term *weight* is probably more familiar to you than *mass*, but the two are related. All objects are attracted to each other by gravity, and the greater their mass, the stronger the attraction between them. The **weight** of an object on Earth is a measurement of the gravitational force pulling the object toward Earth. An object with twice the mass of a second object is attracted with twice the force, and therefore has a weight twice the weight of the second object. The mass of an object is constant, no matter where it is located (even if it is in a weightless condition in outer space). However, the weight of an object depends on the strength of the gravitational attraction to which it is subjected. For example, a rock that weighs 16 pounds on Earth would weigh about 2.7 pounds on the moon (see **Figure 1.1**) because the gravitational attraction on the moon is only about one-sixth that of Earth. However, the rock contains the same amount of matter and thus has the same mass whether it is located on Earth or on the moon.

weight A measurement of the gravitational force acting on an object.

alsen/431 images/Pixabay

FIGURE 1.1 Objects on the moon would weigh about one-sixth of their weight on Earth.

Despite the difference in meaning between mass and weight, the determination of mass is commonly called "weighing." We will follow that practice in this book, but we will use the correct term *mass* when referring to an amount of matter.

1.2 Properties and Changes

Learning Objective 2 Explain the difference between the terms *physical* and *chemical* as applied to the properties of matter and changes in matter.

When you looked at your surroundings earlier, you didn't have much trouble identifying the various things you saw. For example, unless the decorator of your room had unusual tastes, you could easily tell the difference between a TV set and a potted plant by observing characteristics such as shape, color, and size. Our ability to identify objects or materials and discriminate between them depends on such characteristics. Scientists prefer to use the term *property* instead of *characteristic*, and they classify properties into two categories, physical and chemical.

Physical properties are those that can be observed or measured without changing or trying to change the composition of the matter i.e.—no original substances are destroyed, and no new substances appear. For example, you can observe the color or measure the size of a sheet of paper without attempting to change the paper into anything else. Color and size are physical properties (see **Figure 1.2**) of the paper. **Chemical properties** are the properties that matter demonstrates when attempts are made to change it into other kinds of matter. For example, a sheet of paper can be burned; in this process, the paper is changed into a new substance. On the other hand, attempts to burn a piece of glass under similar conditions fail. The ability of paper to burn is a chemical property, as is the inability of glass to burn.

physical properties Properties of matter that can be observed or measured without trying to change the composition of the matter being studied.

chemical properties Properties that matter demonstrates when attempts are made to change it into new substances.

You can easily change the size of a sheet of paper by cutting off a piece. The paper sheet is not converted into any new substance by this change, but it is simply made smaller. **Physical changes** can be carried out without changing the composition of a substance. However, there is no way you can burn a sheet of paper without changing it into new substances. Thus, the change that occurs when paper burns is called a **chemical change. Figure 1.3** shows an example of a chemical change, the burning of magnesium metal. The bright light produced

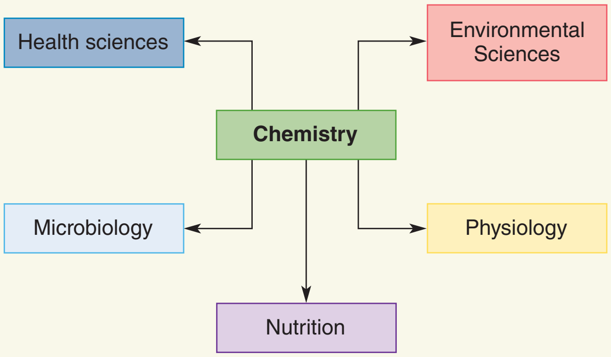
physical changes Changes matter undergoes without changing composition.

chemical changes Changes matter undergoes that involve changes in composition.

ENVIRONMENTAL CONNECTIONS **1.1**

A Central Science

Chemistry is often referred to as the “central science” because it serves as a necessary foundation for many other scientific disciplines. Regardless of which scientific field you are interested in, every single substance you will discuss or work with is made up of chemicals. Also, many processes important to those fields will be based on an understanding of chemistry.



Chemistry is the foundation for many other scientific disciplines.

We also consider chemistry a central science because of its crucial role in responding to the needs of society. We use chemistry to discover new processes, develop new sources of energy, produce new products and materials, provide more food, and ensure better health.

As you read this text, you will encounter chapter-opening applications of chemistry in the health-care professions. Within the chapters, Environmental Connections and Health Connections boxes focus on specific topics that play essential roles in meeting the needs of society.

© Cengage Learning/Charles D. Winters

Chemicals are present in everything we can touch, smell, or see. Chemistry is all around us.

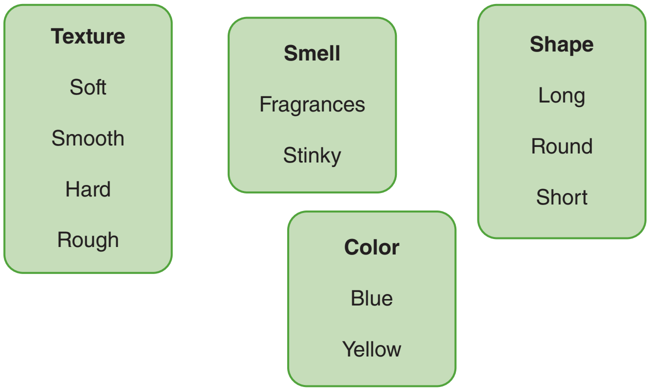


FIGURE 1.2 Some physical properties of matter.

by this chemical change led to the use of magnesium in the flash powder used in early photography. Magnesium is still used in fireworks to produce a brilliant white light.

Example 1.1 Classifying Changes as Physical or Chemical

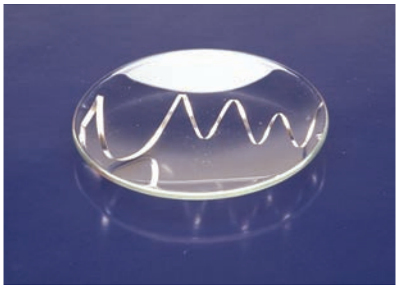
Classify each of the following changes as physical or chemical: (a) a match is burned; (b) iron is melted; (c) limestone is crushed; (d) limestone is heated, producing lime and carbon dioxide; (e) an antacid seltzer tablet is dissolved in water; and (f) a rubber band is stretched.

Solution

Changes b, c, and f are physical changes because no composition changes occurred and no new substances were formed.

The others are chemical changes because new substances were formed as illustrated. A match is burned—combustion gases are given off, and matchstick wood is converted to ashes. Limestone is heated—lime and carbon dioxide are the new substances. A seltzer tablet is dissolved in water—the fizzing that results is evidence that at least one new material (a gas) is produced.

✔ **LEARNING CHECK 1.1** Classify each of the following changes as physical or chemical, and, in the cases of chemical change, describe one observation or test that indicates new substances have been formed: (a) milk sours, (b) a wet handkerchief dries, (c) fruit ripens, (d) a stick of dynamite explodes, (e) air is compressed into a steel container, and (f) water boils.

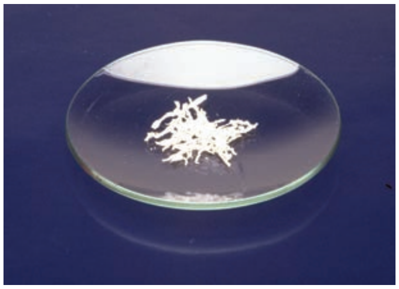


© Cengage Learning/Larry Cameron

1. A strip of magnesium metal.

© Cengage Learning/Larry Cameron

2. After being ignited with a flame, the magnesium burns with a blinding white light.



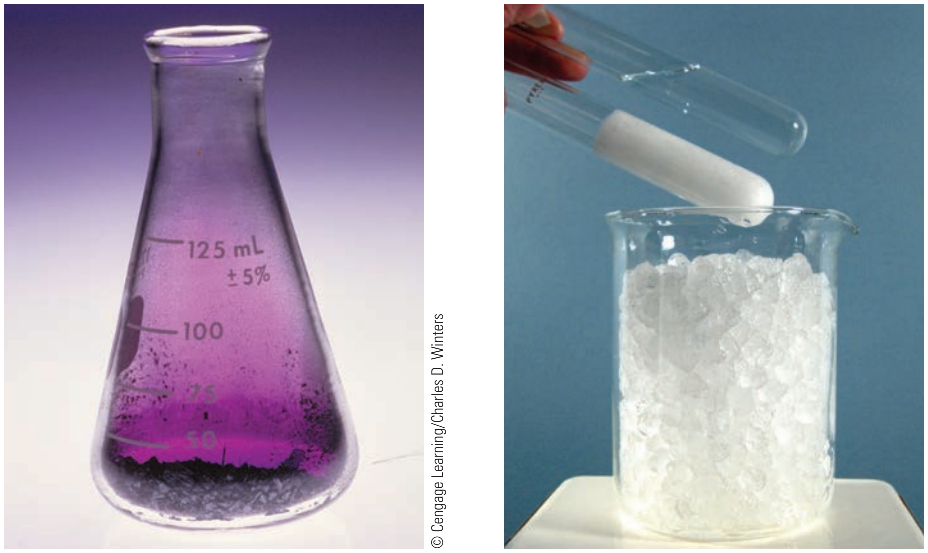
© Cengage Learning/Larry Cameron

3. The white ash of magnesium oxide from the burning of several magnesium strips.

FIGURE 1.3 A chemical change occurs when magnesium metal burns.

Among the most common physical changes are changes in state, such as the melting of solids to form liquids, the sublimation of solids to form gases, or the evaporation of liquids to form gases. These changes take place when heat is added to or removed from matter, as represented in **Figure 1.4**. We will discuss changes in state in more detail in Chapter 6.

FIGURE 1.4 Examples of physical change.



© Cengage Learning/Charles D. Winters

© Jeffrey M. Seager

a Solid iodine becomes gaseous iodine when heated.

b Liquid benzene becomes solid benzene when cooled.

1.3 A Model of Matter

Learning Objective 3 Describe matter in terms of the accepted scientific model.

Model building is a common activity of scientists, but the results in many cases would not look appropriate on a fireplace mantle. **Scientific models** are explanations for observed behavior. Some, such as the well-known representation of the solar system, can easily be depicted in a physical way. Others are so abstract that they can be represented only by mathematical equations.

scientific models Explanations for observed behavior in nature.

Our present understanding of the nature of matter is a model that has been developed and refined over many years. Based on careful observations and measurements of the properties of matter, the model is still being modified as more is learned. In this book, we will concern ourselves with only some very basic concepts of this model, but even then these basic ideas will provide a powerful tool for understanding the behavior of matter.

The study of the behavior of gases—such as air, oxygen, and carbon dioxide—by some of the earliest scientists led to a number of important ideas about matter. The volume of a gas kept at a constant temperature was found to change with pressure. An increase in pressure caused the gas volume to decrease, whereas a decrease in pressure permitted the gas volume to increase. It was also discovered that the volume of a gas maintained at constant pressure increased as the gas temperature was increased. Gases were also found to have mass and ability to mix rapidly with one another when brought together.

Alexandra Lande/Shutterstock.com

FIGURE 1.5 A hang glider soars far above the ground. How does this feat confirm that air is matter?

A simple model for matter was developed that explained these gaseous properties, as well as many properties of solids and liquids. Some details of the model are discussed in Chapter 6, but one conclusion is important to us now I.e., all matter is made up of particles that are too small to see (see **Figure 1.5**). The early framers of this model called the small particles *molecules.* It is now known that molecules are the constituent particles of many, but not in all substances. In this chapter, we will limit our discussion to substances made up of molecules. Substances that are not made of molecules will be discussed in **Sections 4.3** and **4.11**.

The results of some simple experiments will help us formally define the term *molecule.* Suppose you have a container filled with oxygen gas and you perform a number of experiments with it. You find that a glowing splinter of wood bursts into flames when placed in the gas. A piece of moist iron rusts much faster in the oxygen than it does in air. A mouse or other animal can safely breathe the gas.

Now suppose you divide another sample of oxygen, the same size as the first into two smaller samples. The results of similar experiments done with these samples would be the same as before. Continued subdivision of an oxygen sample into smaller and smaller samples does not change the ability of the oxygen in the samples to behave just like the oxygen in the original sample. We conclude that the physical division of a sample of oxygen gas into smaller and smaller samples does not change the oxygen into anything else—it is still oxygen. Is there a limit to such divisions? What is the smallest sample of oxygen that will behave like the larger sample? We hope you have concluded that the smallest sample must be a single molecule. Although its very small size would make a one-molecule sample difficult to handle, it would nevertheless behave just as a larger sample would—it could be stored in a container, it would make wood burn rapidly, it would rust iron, and it could be breathed safely by a mouse.

We are now ready to formally define the term *molecule.* A **molecule** is the smallest particle of a pure substance that has the properties of that substance and is capable of a stable independent existence. Alternatively, a molecule is defined as the limit of physical subdivision for a pure substance.

molecule The smallest particle of a pure substance that has the properties of that substance and is capable of a stable independent existence. Alternatively, a molecule is the limit of physical subdivision for a pure substance.

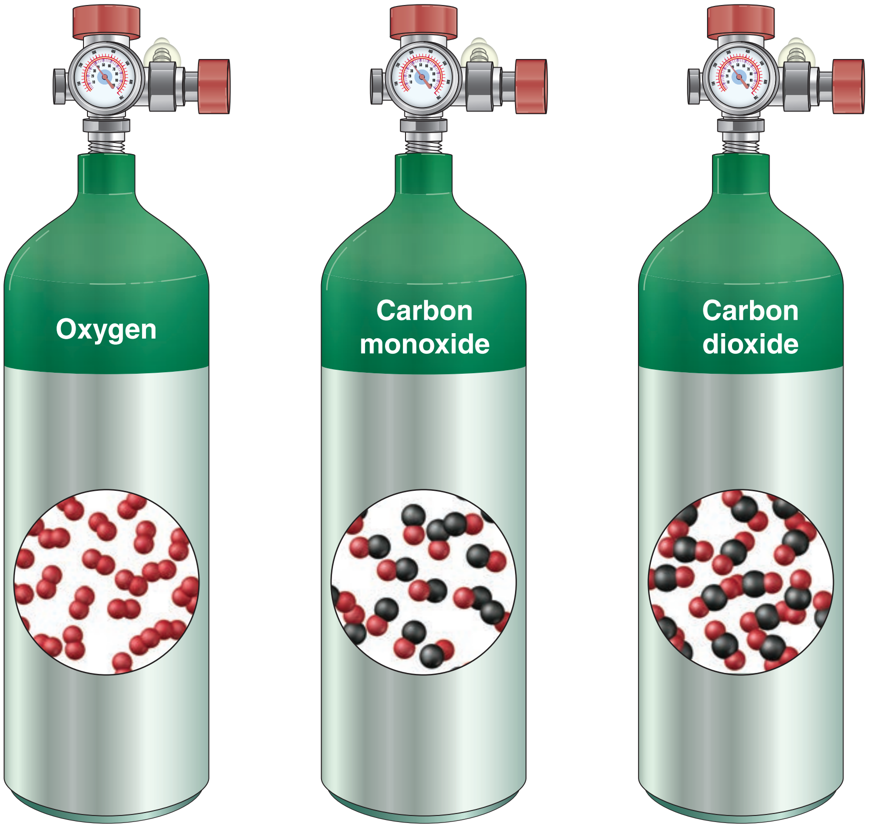
In less formal terms, these definitions indicate that a sample of pure substance—such as oxygen, carbon monoxide, or carbon dioxide—can be physically separated into smaller and smaller samples only until there is a single molecule. Any further separation cannot be done physically, but if it were done (chemically), the resulting sample would no longer have the same properties as the larger sample.

The idea that it might be possible to chemically separate a molecule into smaller particles grew out of continued study and experimentation by early scientists. In modern terminology, the smaller particles that make up molecules are called atoms. John Dalton (1766–1844) is generally credited with developing the first atomic theory containing ideas that are still used today. The main points of his theory, which he proposed in 1808, can be summarized in the following five statements:

1. All matter is made up of tiny particles called atoms.
2. Substances called elements are made up of atoms that are all identical.
3. Substances called compounds are combinations of atoms of two or more elements.
4. Every molecule of a specific compound always contains the same number of atoms of each kind of element found in the compound.
5. In chemical reactions, atoms are rearranged, separated, or combined, but are never created nor destroyed.

Early scientists used graphic symbols such as circles and squares to represent the few different atoms that were known at the time. Instead of different shapes, we will use representations such as those in **Figure 1.6** for oxygen, carbon monoxide, and carbon dioxide molecules.

FIGURE 1.6 Symbolic representations of molecules.



diatomic molecules Molecules that contain two atoms.

homoatomic molecules Molecules that contain only one kind of atom.

heteroatomic molecules Molecules that contain two or more kinds of atoms.

triatomic molecules Molecules that contain three atoms.

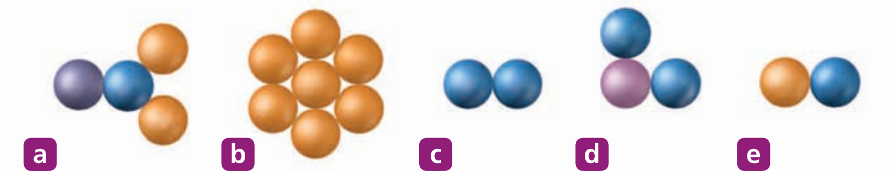
polyatomic molecules Molecules that contain three or more atoms.

The three pure substances just mentioned illustrate three different types of molecules found in matter. Oxygen molecules consist of two oxygen atoms, and are called **diatomic molecules** to indicate that fact. Molecules, such as oxygen, that contain only one kind of atom are also called **homoatomic molecules** to indicate that the atoms are all of the same kind. Carbon monoxide molecules also contain two atoms and therefore are diatomic molecules. However, in this case the atoms are not identical, a fact indicated by the term **heteroatomic molecule**. Carbon dioxide molecules consist of three atoms that are not all identical, so carbon dioxide molecules are described by the terms **triatomic** and heteroatomic. The words *diatomic* and *triatomic* are commonly used to indicate two and three atom molecules respectively, but the word **polyatomic** is usually used to describe molecules that contain more than three atoms.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 1.2 Classifying Molecules

Use the terms *diatomic, triatomic, polyatomic, homoatomic,* or *heteroatomic* to classify the following molecules correctly:



Solution

a. Polyatomic and heteroatomic (contains more than three atoms, and the atoms are not all identical)
b. Polyatomic and homoatomic (more than three atoms, and the atoms are all identical)
c. Diatomic and homoatomic (two atoms, and the atoms are identical)
d. Triatomic and heteroatomic (three atoms, and the atoms are not identical)
e. Diatomic and heteroatomic (two atoms, and the atoms are not identical)

✓ **LEARNING CHECK 1.2** Use the terms *diatomic, triatomic, polyatomic, homoatomic,* or *heteroatomic* to classify the following molecules correctly:

a. Water molecules have been found to contain two hydrogen atoms and one oxygen atom.
b. Molecules of ozone contain three oxygen atoms.
c. Natural gas is made up primarily of methane molecules, which contain one atom of carbon and four atoms of hydrogen.

The subdivision of molecules into smaller particles is a chemical change. How far can such subdivisions of molecules go? You are probably a step ahead of us and have guessed that the answer is atoms. In fact, this provides us with a definition of atoms. An **atom** is the limit of chemical subdivision. In less formal terms, atoms are the smallest particles of matter that can be produced as a result of chemical changes. However, all chemical changes do not necessarily break molecules into atoms. In some cases, chemical changes might just divide a large molecule into two or more smaller molecules. Also, as we will see later, some chemical changes form larger molecules from smaller ones. The important point is that only chemical changes will produce a division of molecules, and the smallest particles of matter that can possibly be produced by such a division are called atoms.

atom The limit of chemical subdivision for matter.

1.4 Classifying Matter

Learning Objective 4 On the basis of observation or information given to you, classify matter into the correct category of each of the following pairs: heterogeneous or homogeneous, solution or pure substance, and element or compound.

Unknown substances are often analyzed to determine their compositions. An analyst, upon receiving a sample to analyze, will always ask an important question: Is the sample a pure substance or a mixture? Any sample of matter must be one or the other. Pure water and sugar are both pure substances, but you can create a mixture by stirring together some sugar and pure water.

What is the difference between a pure substance and a mixture? Two differences are that a **pure substance** has a constant composition (see **Figure 1.7**) and a fixed set of physical and chemical properties. Pure water, for example, always contains the same proportions of hydrogen and oxygen and freezes at a specific temperature. A **mixture** of sugar and water, however, can vary in composition, and the properties will be different for

David Orcea/Shutterstock.com

FIGURE 1.7 A pure substance such as salt has a constant composition, 100%.

pure substance Matter that has a constant composition and fixed properties.

mixture A physical blend of matter that can theoretically be physically separated into two or more components.

different compositions. For example, a glass of sugar water could contain a few crystals of sugar or several spoonfuls. Properties such as the sweetness and freezing point would vary depending on the amount of sugar present in the mixture.

Another difference is that a pure substance cannot be physically separated into simpler substances, whereas a mixture can theoretically be separated into its constituent components. For example, if we heat a sugar-and-water mixture, the water evaporates, and the sugar remains there in. We say that mixtures can theoretically be separated, but some separations are very difficult to achieve. **Figure 1.8** summarizes these ideas.

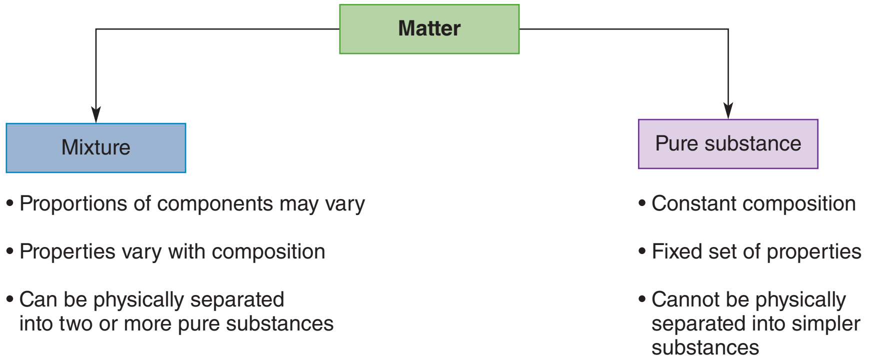

Matter
Mixture
Pure substance
• Proportions of components may vary
• Properties vary with composition
• Can be physically separated into two or more pure substances
• Constant composition
• Fixed set of properties
• Cannot be physically separated into simpler substances

FIGURE 1.8 Mixtures and pure substances.

homogeneous matter Matter that has the same properties throughout the sample.

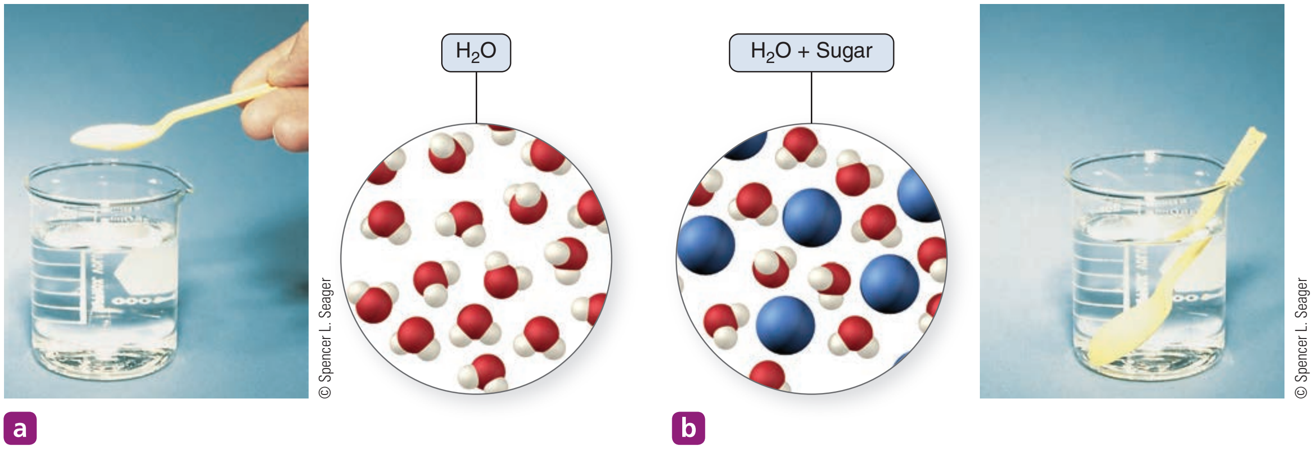
solutions Homogeneous mixtures of two or more pure substances.

heterogeneous matter Matter with properties that are not the same throughout the sample.

Pure substances, and mixtures such as sugar water, are examples of **homogeneous matter**—matter that has a uniform appearance and the same properties throughout. Homogeneous mixtures such as sugar water are called **solutions** (see **Figure 1.9**). Mixtures in which the properties and appearance are not uniform throughout the sample, are examples of **heterogeneous matter**. The mixture of rock salt and sand that is spread on snowy roads during the winter is an example.

Commonly, the word *solution* is used to describe homogeneous liquid mixtures such as sugar water, but solutions of gases and solids also exist. The air around us is a gaseous solution, containing primarily nitrogen and oxygen. The alloys of some metals are solid solutions. For example, small amounts of copper are often added to the gold used in making jewelry. The resulting solid solution is harder than gold and has greater resistance to wear.

Most matter is found in nature in the form of heterogeneous mixtures. The properties of such mixtures depend on the location from which their samples are taken. In some cases,


H_2O
H_2O + Sugar
a
b

© Spencer L. Seager

© Spencer L. Seager

FIGURE 1.9 Sugar and water **(a)** form a solution when mixed **(b)**.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

the heterogeneity is obvious. In a slice of tomato, for example, the parts representing the skin, juice, seeds, and pulp can be easily seen and identified, because they look different. Thus, at least one property (e.g., color or texture) is different for the different parts. However, a sample of clean sand collected from a seashore must be inspected very closely before slight differences in appearance can be seen for different sand particles. At this point, you might be thinking that even the solutions described earlier as homogeneous mixtures would appear to be heterogeneous if they were looked at closely enough. We could differentiate between sugar and water molecules if sugar solutions were observed under high magnification. We will generally limit ourselves to differences normally visible, when we classify matter as heterogeneous on the basis of appearance.

Earlier, we looked at three examples of pure substances—oxygen, carbon monoxide, and carbon dioxide—and found that the molecules of these substances are of different types. Oxygen molecules are diatomic and homoatomic, carbon monoxide molecules are diatomic and heteroatomic, and carbon dioxide molecules are triatomic and heteroatomic. Many pure substances have been found to consist of either homoatomic or heteroatomic molecules—a characteristic that permits them to be classified into one of two categories. Pure substances made up of homoatomic molecules are called **elements**, and those made up of heteroatomic molecules are called **compounds**. Thus, oxygen is an element, whereas carbon monoxide and carbon dioxide are compounds.

element A pure substance consisting of only one kind of atom in the form of homoatomic molecules or individual atoms.

compound A pure substance consisting of two or more kinds of atoms in the form of heteroatomic molecules or individual atoms.

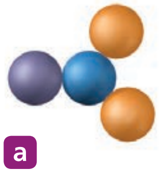
It is useful to note a fact here that is discussed in more detail in **Section 4.11**. The smallest particles of some elements and compounds are individual atoms rather than molecules. However, in elements of this type, the individual atoms are all of the same kind, whereas in compounds, two or more kinds of atoms are involved. Thus, the classification of a pure substance as an element or a compound is based on the fact that only one kind of atom is found in elements and two or more kinds are found in compounds. In both cases, the atoms may be present individually or in the form of homoatomic molecules (elements) or heteroatomic molecules (compounds). Some common household materials are pure substances (elements or compounds), such as aluminum foil, baking soda, table salt, etc. (see **Figure 1.10**).

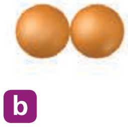
Aluminum Foil
Baking Soda
C&H
Pure
CANE
SUGAR

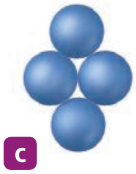
Mike Slabaugh

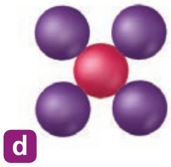
FIGURE 1.10 Sugar, baking soda, and aluminum foil are examples of pure substances found within the home.

✔ **LEARNING CHECK 1.3** Classify the molecules represented below as those of an element or a compound:

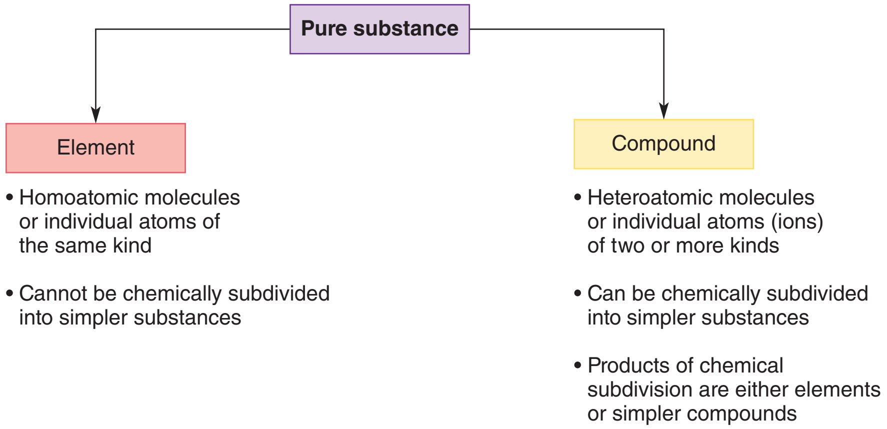








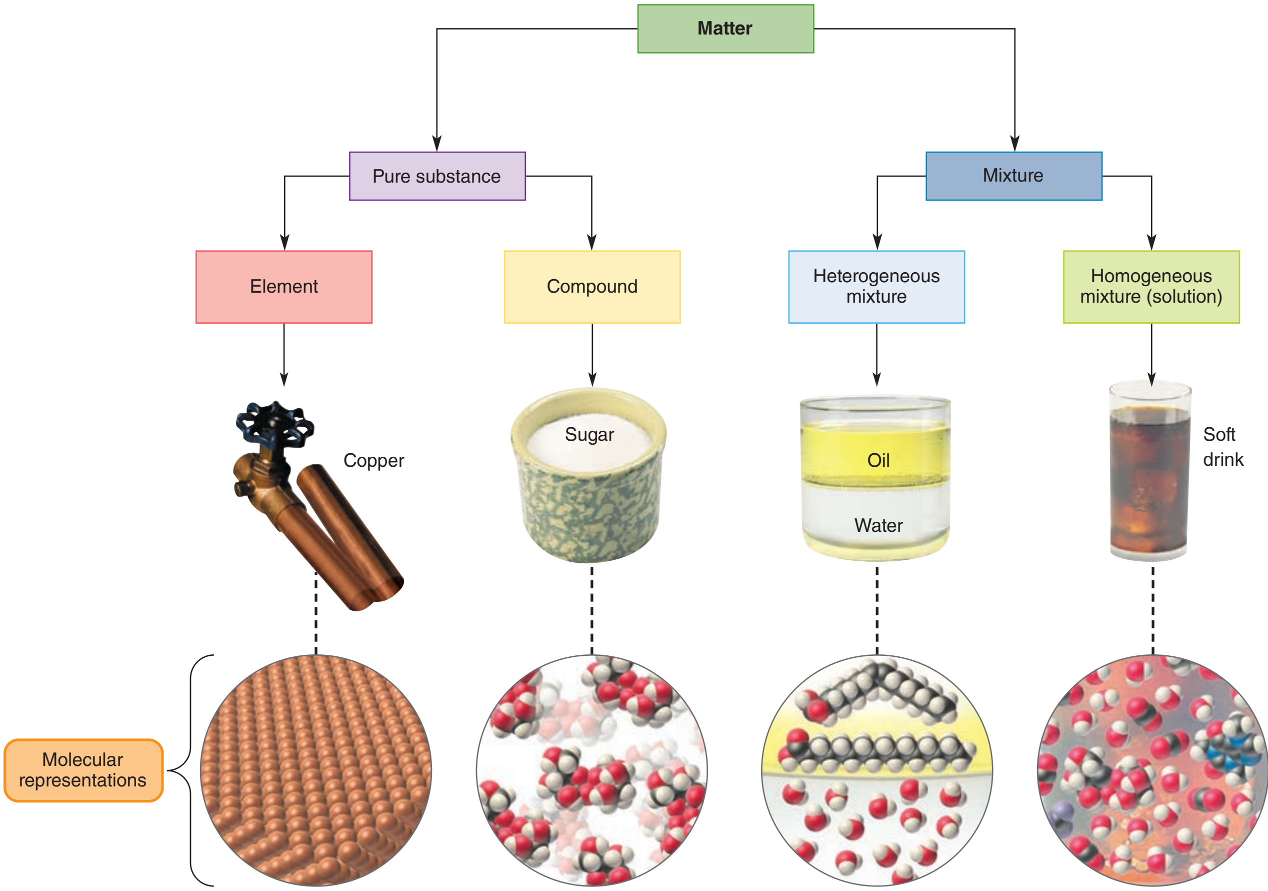
The characteristics of the molecules of elements and compounds lead us to some conclusions about their chemical behavior. Elements cannot be chemically subdivided into simpler pure substances, but compounds can be. Because elements contain only one kind of atom and the atom is the limit of chemical subdivision. There is no chemical way to break an element into any simpler pure substance—the simplest pure substance is an element itself. On the other hand, because the molecules of compounds contain more than one kind of atom, breaking such molecules into simpler pure substances is possible. For example, a molecule of table sugar can be chemically changed into two simpler molecules (which are also sugars) or into atoms or molecules of the elements carbon, hydrogen, and oxygen. Thus, compounds can be chemically subdivided into simpler compounds or elements. **Figure 1.11** summarizes these ideas, and **Figure 1.12** illustrates a classification scheme for matter based on the ideas we have discussed.


Pure substance
Element
Compound

- Homoatomic molecules or individual atoms of the same kind
- Cannot be chemically subdivided into simpler substances

- Heteroatomic molecules or individual atoms (ions) of two or more kinds
- Can be chemically subdivided into simpler substances
- Products of chemical subdivision are either elements or simpler compounds

FIGURE 1.11 Elements and compounds.


Matter
Pure substance
Mixture
Element
Compound
Heterogeneous mixture
Homogeneous mixture (solution)
Copper
Sugar
Oil
Water
Soft drink
Molecular representations

© Photodisc/Getty Images; © Progressive Publishing Alternatives

FIGURE 1.12 A classification scheme for matter.

Example 1.3 Classifying Substances

When sulfur, an element, is heated in air, it combines with oxygen to form sulfur dioxide. Classify whether sulphur dioxide is an element or a compound.

Solution

Because sulfur and oxygen are both elements and they combine to form sulfur dioxide, the molecules of sulfur dioxide must contain atoms of both sulfur and oxygen. Thus, sulfur dioxide is a compound because its molecules are heteroatomic.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

✔ **LEARNING CHECK 1.4** Suppose an element and a compound combine to form only one product. Classify whether the product is an element or a compound.

1.5 Measurement Units

Learning Objective 5 Recognize the use of measurement units in everyday activities.

Matter can be classified and some physical or chemical properties can be observed without making any measurement. However, the use of quantitative measurements and calculations greatly expands our ability to understand the chemical nature of the world around us. A measurement consists of two parts, a number and an identifying unit. A number expressed without a unit is generally useless, especially in scientific work. We constantly make and express measurements in our daily lives. We measure the gallons of gasoline put into our cars, the time it takes to drive a certain distance, and the temperature on a hot or cold day. In some of our daily measurements, the units might be implied or understood. For example, if someone said the temperature outside was 39, you would probably assume this was 39 degrees Fahrenheit if you lived in the United States, but in most other parts of the world, it would be 39 degrees Celsius. Such confusion is avoided by expressing both the number and the unit of a measurement.

All measurements are based on units agreed on by those making and using the measurements. When a measurement is made in terms of an agreed-on unit, the result is expressed as some multiple of that unit. For example, when you purchase 10 pounds of potatoes, you are buying a quantity of potatoes equal to 10 times the standard quantity called 1 pound. Similarly, 3 feet of string is a length of string 3 times as long as the standard length that has been agreed on and called 1 foot.

The earliest units used for measurements were based on the dimensions of the human body. For example, the foot was the length of some important person's foot, and the biblical cubit (see **Figure 1.13**) was the length along the forearm from the elbow to the tip of the middle finger. One problem with such units is obvious; the size of the units changed when the person on whom they were based changed because of death, change in political power, and so on.

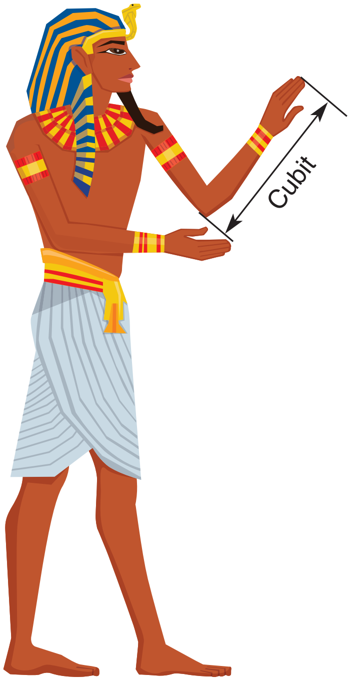


FIGURE 1.13 In ancient cultures, a cubit could vary from 18 to 21 inches, depending on the length of the arm.

As science became more quantitative, scientists found that the lack of standard units became more and more of a problem. A standard system of units was developed in France about the time of the French Revolution and was soon adopted by scientists throughout the world. This system, called the *metric system*, has since been adopted and is used by almost all nations of the world. The United States adopted the system but has not yet put it into widespread use.

In an attempt to further standardize scientific measurements, an international agreement in 1960 established certain basic metric units, and units derived from them, as preferred units to be used in scientific measurements. Measurement units in this system are known as SI units after the French Système International d'Unités. SI units have not yet been totally put into widespread use. Many scientists continue to express certain quantities, such as volume, in non-SI units. The metric system in this book is generally based on accepted SI units but also includes a few of the commonly used non-SI units.

1.6 The Metric System

Learning Objective 6 Recognize units of the metric system, and convert the measurements done, by using the metric system into related units.

The metric system has a number of advantages compared to other measurement systems. One of the most useful among all the advantages is that the metric system is a decimal system in which larger and smaller units of a quantity are related by factors of 10.

FIGURE 1.14 Some things that are about 1 meter in length.

See **Table 1.1** for a comparison between the metric and English units of length—a meter is slightly longer than a yard (see **Figure 1.14**). Notice in **Table 1.1** that the units of length in the metric system are related by multiplying a specific number by 10—remember, 100 = 10 × 10 and 1000 = 10 × 10 × 10. The relationships between the units of the English system show no such pattern.

TABLE 1.1 Metric and English Units of Length

	Base Unit	Larger Unit	Smaller Unit
Metric	1 meter	1 kilometer = 1000 meters	10 decimeters = 1 meter 100 centimeters = 1 meter 1000 millimeters = 1 meter
English	1 yard	1 mile = 1760 yards	3 feet = 1 yard 36 inches = 1 yard

basic unit of measurement A specific unit from which other units for the same quantity are obtained by multiplication or division.

The relationships between units of the metric system that are larger or smaller than a **basic** (defined) **unit** are indicated by prefixes attached to the name of the basic unit. Thus, 1 kilometer (km) is a unit of length that is 1000 times longer than the basic unit of 1 meter (m), and a millimeter (mm) is only $\frac{1}{1000}$ the length of 1 m. Some commonly used prefixes are given in **Table 1.2**.

TABLE 1.2 Common Prefixes of the Metric System

Prefix[a]	Abbreviation	Relationship to Basic Unit	Exponential Relationship to Basic Unit[b]
mega-	M	1,000,000 × basic unit	10^6 × basic unit
kilo-	k	1000 × basic unit	10^3 × basic unit
deci-	d	1/10 × basic unit	10^{-1} × basic unit
centi-	c	1/100 × basic unit	10^{-2} × basic unit
milli-	m	1/1000 × basic unit	10^{-3} × basic unit
micro-	μ	1/1,000,000 × basic unit	10^{-6} × basic unit
nano-	n	1/1,000,000,000 × basic unit	10^{-9} × basic unit
pico-	p	1/1,000,000,000,000 × basic unit	10^{-12} × basic unit

[a] The prefixes in boldface (heavy) type are the most common ones. [b] The use of exponents to express large and small numbers is discussed in **Section 1.7**.

derived unit of measurement A unit obtained by multiplication or division of one or more basic units.

Area and volume are examples of **derived units** of measurement. They are obtained or derived from the basic unit of length as given below:

$$\text{area} = (\text{length})(\text{length}) = (\text{length})^2$$

$$\text{volume} = (\text{length})(\text{length})(\text{length}) = (\text{length})^3$$

The unit used to express an area or volume depends on the unit of length used.

Example 1.4 Calculating Areas

Calculate the area of a rectangle that has sides of 1.5 m and 2.0 m. Express the answer in units of square meters and square centimeters.

Solution

When working examples and exercises with calculations, it is important to use a stepwise approach. Learning the strategy here will help you in the future to deal with more challenging questions.

STEP 1 Examine the question for what is given and what is unknown.

Given: sides are 1.5 m and 2.0 m Unknown: area = ?

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{area} = (\text{length})(\text{length})$$

STEP 3 Enter the data into the formula.

$$\text{area} = (1.5\ \text{m})(2.0\ \text{m}) = 3.0\ \text{m}^2$$

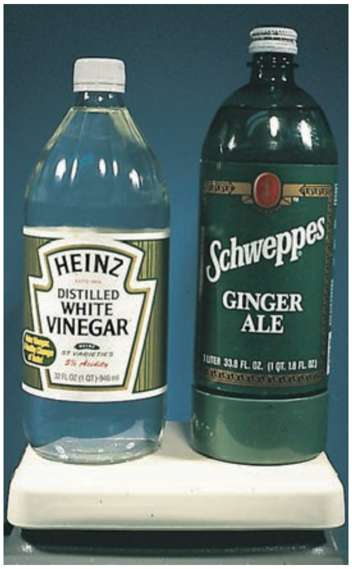
In **Table 1.1**, it is given that 1 m = 100 cm. In terms of centimeters, the lengths are 150 cm and 200 cm.

$$\text{area} = (150\ \text{cm})(200\ \text{cm}) = 30{,}000\ \text{cm}^2$$

STEP 4 Check to see whether your answer makes sense.
Yes. The values seem to be in a reasonable range.

> **✔ LEARNING CHECK 1.5** The area of a circle is given by the formula $A = \pi r^2$, where r is the radius and $\pi = 3.14$. Calculate the area of a circle that has a radius of 3.5 cm.

The unit used to express volume also depends on the unit of length used in the calculation. Thus, a volume could have such units as cubic meters (m^3), cubic decimeters (dm^3), or cubic centimeters (cm^3). The abbreviation cc is also used to represent cubic centimeters, especially in medical work. The liter (L), a non-SI unit of volume, has been used as a basic unit of volume by chemists for many years (see **Figure 1.15**). For all practical purposes, 1 L and 1 dm^3 are equal volumes. This also means that 1 milliliter (mL) is equal to 1 cm^3. Most laboratory glassware is calibrated in liters or milliliters.



© Spencer L. Seager

FIGURE 1.15 A liter is slightly larger than a quart.

Example 1.5 Expressing Volume in Metric Units

Laboratory tests for substances present in blood are often reported in mass per deciliter. From **Table 1.2**, we obtain the numerical relationship that deciliter (dL) = 0.1 liter (L). Express a volume of 1.36 L in terms of dL.

Solution

Because 1 dL = 0.1L, 1.36L can be converted to deciliters as

$$1.36\ \cancel{\text{L}} \times \frac{1\ \text{dL}}{0.1\ \cancel{\text{L}}} = 13.6\ \text{dL}$$

The units of the original quantity (1.36 L) were canceled, and the desired units (dL) were generated by the application of the factor-unit method (see **Section 1.9**).

The basic unit of mass in the metric system is 1 kilogram (kg), which is equal to about 2.2 pounds in the English system. A kilogram is too large to be conveniently used in some applications, so it is subdivided into smaller units. Two of these smaller units that are often used in chemistry are the gram (g) and milligram (mg) (see **Figure 1.16**). The prefixes *kilo-* (k) and *milli-* (m) indicate the following relationships between these units:

$$1\ \text{kg} = 1000\ \text{g}$$

$$1\ \text{g} = 1000\ \text{mg}$$

$$1\ \text{kg} = 1{,}000{,}000\ \text{mg}$$

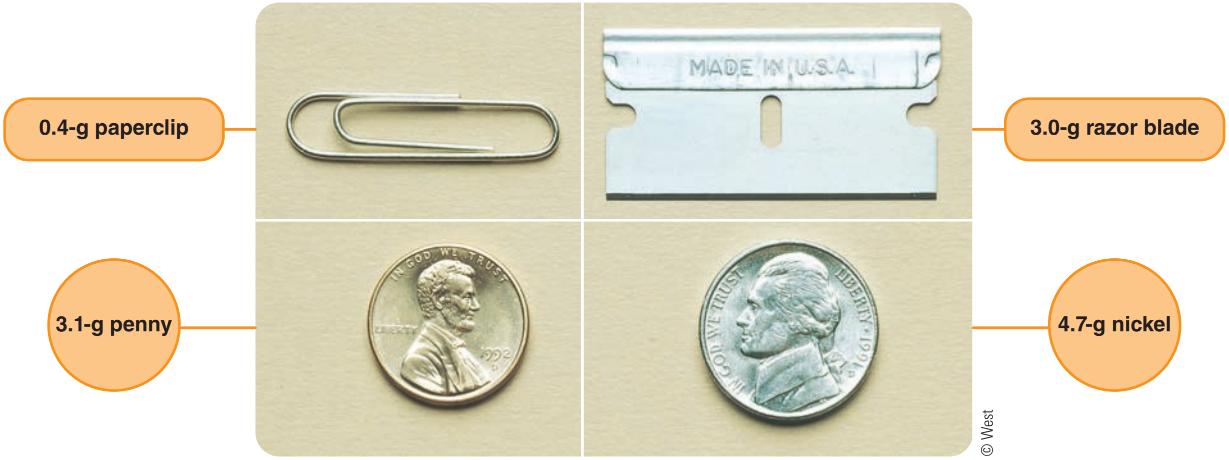


FIGURE 1.16 Metric masses of some common items as found in a 0.4-g paperclip, 3.0-g razor blade, 3.1-g penny, and 4.7-g nickel.

Example 1.6 Expressing Measurements in Metric Units

Saline solution for intravenous infusion is used to treat dehydration and has a number of other important uses in medicine. A partial bag of saline solution has a mass of 600 grams. Express this mass in kilograms and milligrams.

Solution

Since 1 kg = 1000 g, 600 g can be converted to kilograms as follows:

$$600\ \cancel{g} \times \frac{1\ \text{kg}}{1000\ \cancel{g}} = 0.600\ \text{kg}$$

Also, because 1 g = 1000 mg,

$$600\ \cancel{g} \times \frac{1000\ \text{mg}}{1\ \cancel{g}} = 600{,}000\ \text{mg}$$

Once again, the units of the original quantity (600 g) were canceled, and the desired units were generated by the application of the factor-unit method (see **Section 1.9**).

✔ **LEARNING CHECK 1.6** The javelin thrown by male competitors in track and field meets must have a minimum mass of 0.800 kg. A javelin is weighed and found to have a mass of 0.819 kg. Express the mass of the weighed javelin in grams.

Temperature is difficult to define but easy for most of us to measure—we just read a thermometer. However, thermometers can have temperature scales that represent different units. For example, a temperature of 293 would probably be considered quite high until it was pointed out that it is just room temperature as measured using the Kelvin temperature scale. Temperatures on this scale are given in kelvins, K. (Note that the abbreviation is K, not °K.)

The Celsius scale (formerly known as the centigrade scale) is the temperature scale used in most scientific work. On this scale, water freezes at 0°C and boils at 100°C under normal atmospheric pressure. A Celsius degree (division) is the same size as a kelvin of the Kelvin scale, but the two scales have different zero points. **Figure 1.17** compares the two scientific temperature scales and the familiar Fahrenheit scale. There are 100 Celsius degrees (divisions) between the freezing point (0°C) and the boiling point (100°C) of water. On the Fahrenheit scale, these same two temperatures are 180 degrees (divisions) apart

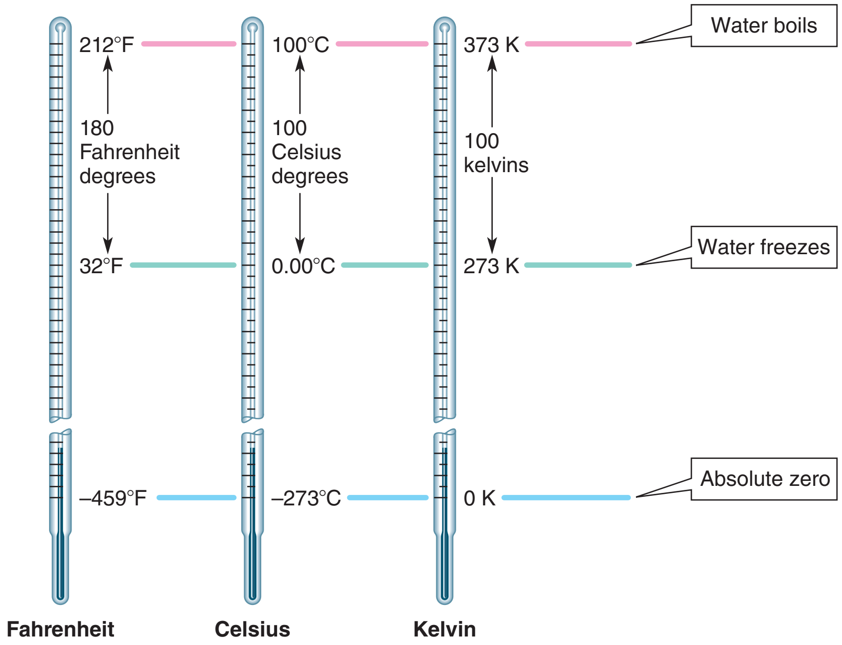

Water boils
212°F
100°C
373 K
180
Fahrenheit
degrees
100
Celsius
degrees
100
kelvins
Water freezes
32°F
0.00°C
273 K
Absolute zero
−459°F
−273°C
0 K
Fahrenheit
Celsius
Kelvin

FIGURE 1.17 Fahrenheit, Celsius, and Kelvin temperature scales. The lowest temperature possible is absolute zero, 0 K.

(the freezing point is 32°F and the boiling point is 212°F). Readings on these two scales are related by the following equations:

$$°\mathrm{C} = \frac{5}{9}(°\mathrm{F} - 32) \tag{1.1}$$

$$°\mathrm{F} = \frac{9}{5}(°\mathrm{C}) + 32° \tag{1.2}$$

As mentioned, the difference between the Kelvin and Celsius scales is simply the zero point. Consequently, readings on the two scales are related as follows:

$$°\mathrm{C} = \mathrm{K} - 273 \tag{1.3}$$

$$\mathrm{K} = °\mathrm{C} + 273 \tag{1.4}$$

Notice that Equation 1.2 can be obtained by solving Equation 1.1 for Fahrenheit degrees, and Equation 1.4 can be obtained by solving Equation 1.3 for kelvins. Thus, you need to remember only Equations 1.1 and 1.3, rather than all four.

Example 1.7 Converting Fahrenheit and Celsius Temperatures

A mother is worried about her child, who has a temperature of 100.8°F. What reading would be shown if a Celsius thermometer were used?

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: 100.8°F

Unknown: °C = ?

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{Key Equation 1.1: } °\mathrm{C} = \frac{5}{9}(°\mathrm{F} - 32)$$

STEP 3 Enter the data into the formula.

$$^\circ\mathrm{C} = \frac{5}{9}(100.8^\circ - 32^\circ) = \frac{5}{9}(68.8^\circ) = 38.2^\circ\mathrm{C}$$

STEP 4 Check to see whether the answer makes sense.

Yes. °C is less than half of °F.

✔ **LEARNING CHECK 1.7** Body temperature is considered to be 37.0°C when measured orally. What reading would be shown if a Fahrenheit thermometer were used?

The last units discussed at this point are derived units of energy. Other units will be introduced later in the book as they are needed. The metric system unit of energy is a joule (J), pronounced "jewl." A joule is quite small, as shown by the fact that a 50-watt light-bulb uses 50 J of energy every second. A typical household in the United States uses several billion joules of electrical energy in a month.

The calorie (cal), a slightly larger unit of energy, is sometimes used by chemists. One calorie is the amount of heat energy required to increase the temperature of 1 g of water by 1°C. The calorie and joule are related as follows:

$$1\ \mathrm{cal} = 4.184\ \mathrm{J}$$

The nutritional calorie of the weight watcher is actually 1000 scientific calories, or 1 kcal. It is represented by writing *calorie* with a capital C (Calorie, abbreviated Cal). **Table 1.3** contains a list of the commonly used metric units, their relationship to basic units, and their relationship to English units.

TABLE 1.3 Commonly Used Metric Units

Quantity	Metric Unit	Relationship to Metric Basic Unit	Relationship to English Unit
Length	meter (m)	Basic unit	1 m = 1.094 yd
	centimeter (cm)	100 cm = 1 m	1 cm = 0.394 in.
	millimeter (mm)	1000 mm = 1 m	1 mm = 0.0394 in.
	kilometer (km)	1 km = 1000 m	1 km = 0.621 mi
Volume	cubic decimeter (dm^3)	Basic unit	1 dm^3 = 1.057 qt
	cubic centimeter (cm^3 or cc)	1000 cm^3 = 1 dm^3	1 cm^3 = 0.0338 fl oz
	liter (L)	1 L = 1 dm^3	1 L = 1.057 qt
	milliliter (mL)[a]	1000 mL = 1 dm^3	1 mL = 0.0338 fl oz
Mass	gram (g)	1000 g = 1 kg	1 g = 0.035 oz
	milligram (mg)	1,000,000 mg = 1 kg	1 mg = 0.015 grain
	kilogram (kg)	Basic unit	1 kg = 2.20 lb
Temperature	degree Celsius (°C)	1°C = 1 K	1°C = 1.80°F
	kelvin (K)	Basic unit	1 K = 1.80°F
Energy	calorie (cal)	1 cal = 4.184 J	1 cal = 0.00397 BTU[b]
	kilocalorie (kcal)	1 kcal = 4184 J	1 kcal = 3.97 BTU
	joule (J)	Basic unit	1 J = 0.000949 BTU
Time	second (s)	Basic unit	Same unit used

[a] 1 mL = 1 cm^3. [b] A BTU (British thermal unit) is the amount of heat required to increase the temperature of 1 pound of water by 1°F.

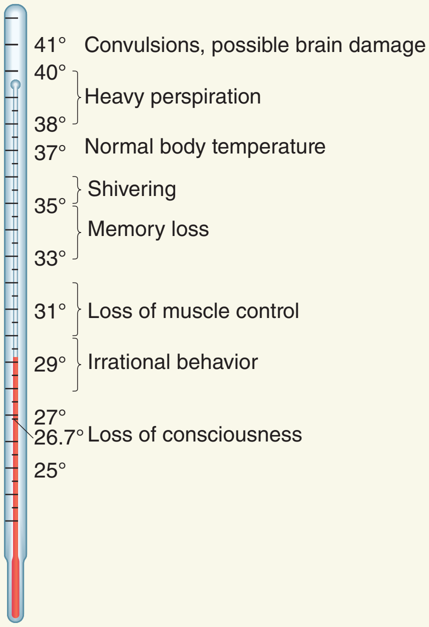
HEALTH CONNECTIONS 1.1

Effects of Temperature on Body Functions

The human body has the ability to remain at a relatively constant temperature even when the surrounding temperature increases or decreases. Because of this characteristic, we humans are classified as warm-blooded. In reality, our body temperature varies over a significant range depending on the time of day and the temperature of our surroundings. "Normal" body temperature is considered to be 37.0°C when measured orally. However, this "normal" value can fluctuate between a low of 36.1°C for an individual just waking up in the morning to a value as high as 37.2°C just before bedtime in the late evening.

In addition to this regular variation, our body temperature fluctuates in response to extremes in the temperature of our surroundings. In extremely hot environments, the capacity of our perspiration-based cooling mechanism can be overtaxed, and our body temperature will increase. Body temperatures more than 3.5°C above normal begin to interfere with bodily functions. Body temperatures above 41.1°C can cause convulsions and can result in permanent brain damage, especially in children.

Hypothermia occurs when the body's internal heat generation is not sufficient to balance the heat lost to very cold surroundings. As a result, the body temperature decreases, and at 28.5°C the afflicted person appears pale and might have an irregular heartbeat. Unconsciousness usually results if the body temperature gets lower than 26.7°C. At these low temperatures, respiration also slows down and becomes shallow, resulting in a decrease in the delivery of oxygen to the body tissues.


41° Convulsions, possible brain damage
40°
Heavy perspiration
38°
37° Normal body temperature
Shivering
35°
Memory loss
33°
31° Loss of muscle control
29° Irrational behavior
27°
26.7° Loss of consciousness
25°

The effects of body temperature on body functions using the Celsius scale.

1.7 Large and Small Numbers

Learning Objective 7 Express numbers using scientific notation, and do calculations with numbers expressed in scientific notation.

Numbers are used in all measurements and calculations. Many numbers are readily understood and represented because of common experience with them. A price of 10 dollars, a height of 7 feet, a weight of 165 pounds, and a time of 40 seconds are examples of such numbers. But how do we handle numbers like the diameter of a hydrogen atom (about one hundred-millionth of a centimeter) or the distance light travels in 1 year—a light-year (about 6 trillion miles)? These numbers are so small and large, respectively, that they defy understanding in terms of relationships to familiar distances. Even if we can't totally relate to them, it is important in scientific work to be able to conveniently represent and work with such numbers.

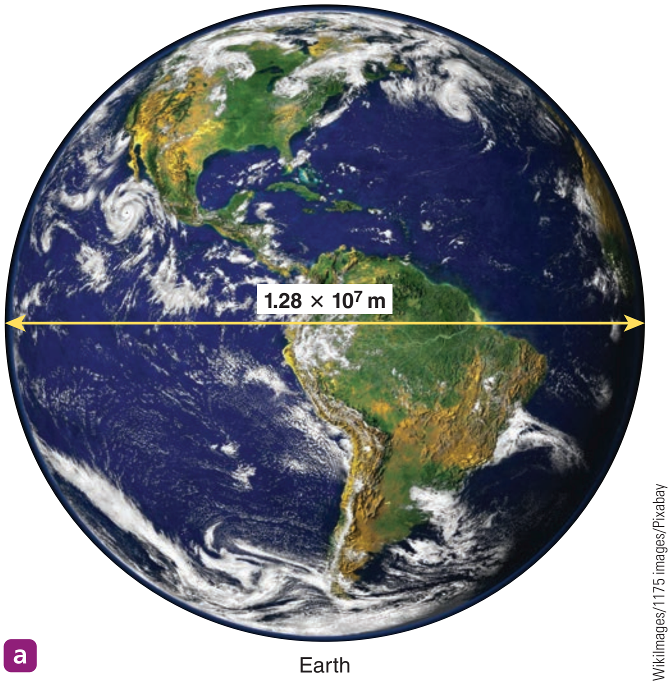
Scientific notation provides a method for conveniently representing any number including those that are very large or very small. In **scientific notation**, numbers are represented as the product of a non-exponential term and an exponential term in the general form $M \times 10^n$. The non-exponential term M is a number between 1 and 10 (but not equal to 10) written with a decimal to the right of the first nonzero digit in the number. This position of the decimal is called the **standard position**. The exponential term is a 10 raised to a whole number exponent n that may be positive or negative. The value of n is the number

scientific notation A way of representing numbers consisting of a product between a nonexponential number and 10 raised to a whole-number exponent that may be positive or negative.

standard position for a decimal In scientific notation, the position to the right of the first nonzero digit in the nonexponential number.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

of places the decimal must be moved from the standard position in *M* to be at the original position in the number when the number is written normally without using scientific notation. If *n* is positive, the original decimal position is to the right of the standard position [see **Figure 1.18(a)**]. If *n* is negative, the original decimal position is to the left of the standard position [see **Figure 1.18(b)**].



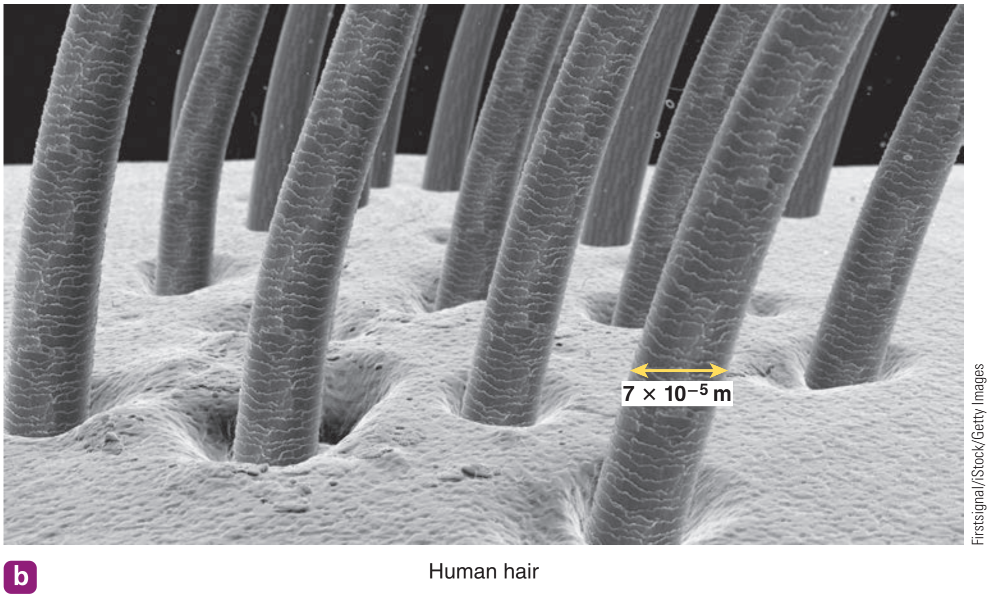


FIGURE 1.18 **(a)** The equatorial diameter of Earth is 1.28×10^7 meters. **(b)** The width of human hair varies depending on thickness. For average hair, the width is about 7×10^{-5} meters.

Example 1.8 Converting Scientific Notation to Non-scientific

Very small numbers such as the diameter of a bacterium and very large numbers such as the number of viral particles in a sample are expressed using scientific notation.

The following numbers are written using scientific notation. Write them without using scientific notation.

a. 3.72×10^5 b. 8.513×10^{-7}

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Solution

a. The exponent 5 indicates that the new position of the decimal is located 5 places to the right of the standard position. Zeros are added to accommodate this change:

$$3.72 \times 10^5 = 3\overset{\nearrow}{.}72{,}000. = 372{,}000$$

standard position   new position

b. The exponent −7 indicates that the new position of the decimal is 7 places to the left of the standard position. Again, zeros are added as needed:

$$8.513 \times 10^{-7} = 0.0000008.513$$

new position   standard position

Example 1.9 Converting Non-scientific Notation to Scientific

Write the following numbers using scientific notation:

a. 8725.6   b. 0.000729

Solution

a. The standard decimal position is between the 8 and 7: 8.7256. However, the original position of the decimal is 3 places to the right of the standard position. Therefore, the exponent must be +3:

$$8725.6 = 8.7256 \times 10^3$$

standard position   original position is to the right (+3)   exponent is positive for numbers greater than 1.0

b. The standard decimal position is between the 7 and 2: 7.29. However, the original position is 4 places to the left of standard. Therefore, the exponent must be −4:

$$0.000729 = 7.29 \times 10^{-4}$$

original position is to the left (−4)   standard position   exponent is negative for numbers less than 1.0

The zeros to the left of the 7 are dropped because they are not significant figures (see **Section 1.8**); they only locate the decimal in the nonscientific notation and are not needed in the scientific notation.

✔ LEARNING CHECK 1.8 Some of the following numbers are written using scientific notation, and some are not. In each case, rewrite the numbers using the notation in which it is not written.

a. 5.88×10^2
b. 0.000439
c. 3.915×10^{-4}
d. 9870
e. 36.77
f. 0.102

Example 1.10 Recognizing Scientific Notation

Determine which of the following numbers are written correctly using scientific notation. For those that are not, rewrite them correctly.

a. 001.5×10^{-3} b. 28.0×10^{2} c. 0.35×10^{4}

Solution

a. Incorrect; the zeros to the left are not needed. The correct answer is 1.5×10^{-3}.
b. Incorrect; the decimal is not in the standard position. Move the decimal one position to the left and increase the exponent by 1 to give the correct answer of 2.80×10^{3}.
c. Incorrect; the decimal is not in the standard position. Move the decimal one position to the right and decrease the exponent by 1 to give the correct answer of 3.5×10^{3}.

✔ **LEARNING CHECK 1.9** Determine which of the following numbers are written correctly using scientific notation. For those that are not, rewrite them correctly.

a. 62.5×10^{4} b. 0.0098 c. 0.0041×10^{-3} d. 7.85×10^{2}

The multiplication and division of numbers written in scientific notation can be done quite simply by using some characteristics of exponentials. Consider the following multiplication:

$$(a \times 10^{y})(b \times 10^{z})$$

The multiplication is done in two steps. First, the nonexponential terms a and b are multiplied in the usual way. The exponential terms 10^{y} and 10^{z} are multiplied by adding the exponents y and z and using the resulting sum as a new exponent of 10. Thus, we can write

$$(a \times 10^{y})(b \times 10^{z}) = (a \times b)(10^{y+z})$$

Division is done similarly. The nonexponential terms are divided in the usual way, and the exponential terms are divided by subtracting the exponent of the bottom term from that of the top term. The final answer is then written as a product of the resulting nonexponential and exponential terms:

$$\frac{a \times 10^{y}}{b \times 10^{z}} = \left(\frac{a}{b}\right)(10^{y-z})$$

Multiplication and division calculations involving scientific notation are easily done using a calculator. **Table 1.4** gives the steps, the typical calculator procedures (buttons to press), and typical calculator readout or display for the division of 7.2×10^{-3} by 1.2×10^{4}.

TABLE 1.4 Using a Calculator for Scientific Notation Calculations

Step	Procedure		Calculator Display
1. Enter 7.2	Press buttons 7, ., 2	7 . 2	7.2
2. Enter 10^{-3}	Press button that activates exponential mode (EE, Exp, etc.)	EE , EXP	7.2^{00}
	Press 3	3	7.2^{03}
	Press change-sign button (±, etc.)	+/-	7.2^{-03}
3. Divide	Press divide button (÷)	÷	7.2^{-03}
4. Enter 1.2	Press buttons 1, ., 2	1 . 2	1.2
5. Enter 10^{4}	Press button that activates exponential mode (EE, Exp, etc.)	EE , EXP	1.2^{00}
	Press 4	4	1.2^{04}
6. Obtain answer	Press equals button (=)	=	$6.^{-07}$

Example 1.11 More Exercises with Scientific Notation

Do the following operations:

a. $(3.5 \times 10^4)(2.0 \times 10^2)$

b. $\dfrac{3.8 \times 10^5}{1.9 \times 10^2}$

c. $(4.6 \times 10^{-7})(5.0 \times 10^3)$

d. $\dfrac{1.2 \times 10^3}{3.0 \times 10^{-2}}$

Solution

a. $$\begin{aligned}(3.5 \times 10^4)(2.0 \times 10^2) &= (3.5 \times 2.0)(10^4 \times 10^2)\\ &= (7.0)(10^{4+2}) = 7.0 \times 10^6\end{aligned}$$

b. $$\frac{3.8 \times 10^5}{1.9 \times 10^2} = \frac{3.8}{1.9} \times \frac{10^5}{10^2} = (2.0)(10^{5-2}) = 2.0 \times 10^3$$

c. $$\begin{aligned}(4.6 \times 10^{-7})(5.0 \times 10^3) &= (4.6 \times 5.0)(10^{-7} \times 10^3)\\ &= (23)(10^{-7+3}) = 23 \times 10^{-4}\end{aligned}$$

To get the decimal into the standard position, move it one place to the left. This changes the exponent from -4 to -3, so the final result is 2.3×10^{-3}. (This number in decimal form, 0.0023, can be written correctly as either 23×10^{-4} or 2.3×10^{-3}, but scientific notation requires that the decimal point should be to the right of the first nonzero number.)

d. $$\frac{1.2 \times 10^3}{3.0 \times 10^{-2}} = \frac{1.2}{3.0} \times \frac{10^3}{10^{-2}} = (0.40)(10^{3-(-2)}) = 0.40 \times 10^5$$

Adjust the decimal to the standard position and get 4.0×10^4. If these examples were done using a calculator, the displayed answers would normally be given in correct scientific notation.

✔ **LEARNING CHECK 1.10** Perform the following operations, and express the result in correct scientific notation:

a. $(2.4 \times 10^3)(1.5 \times 10^4)$

b. $(3.5 \times 10^2)(2.0 \times 10^{-3})$

c. $\dfrac{6.3 \times 10^5}{2.1 \times 10^3}$

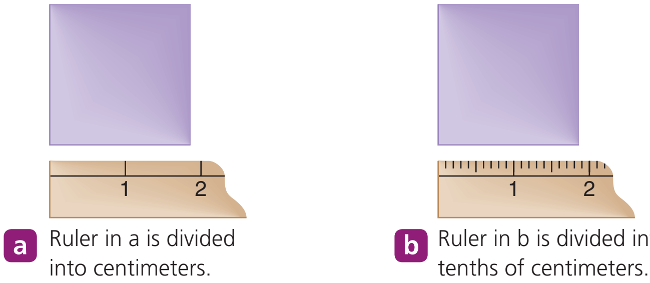
d. $\dfrac{4.4 \times 10^{-2}}{8.8 \times 10^{-3}}$

The diameter of a hydrogen atom, mentioned earlier as one hundred-millionth of a centimeter, is written in scientific notation as 1.0×10^{-8} cm. Similarly, 1 light-year of 6 trillion miles is 6.0×10^{12} mi.

1.8 Significant Figures

Learning Objective 8 Express the results of measurements and calculations using the correct number of significant figures.

Every measurement contains an uncertainty that is characteristic of the device used to make the measurement. These uncertainties are represented by the numbers used to record the measurement. Consider the small square in **Figure 1.19**:



a Ruler in a is divided into centimeters.

b Ruler in b is divided into tenths of centimeters.

FIGURE 1.19 Measurements using two different rulers.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

In (a), the length of one side of the square is measured with a ruler divided into centimeters. It is easy to see that the length is greater than 1 cm, but not quite 2 cm. The length is recorded by writing the number that is known with certainty to be correct (the 1) and writing an estimate for the uncertain number. The result is 1.9 cm, where the .9 is the estimate. In (b), the ruler is divided into tenths of centimeters. It is easy to see that the length is at least 1.8 cm, but not quite 1.9 cm. Once again the certain numbers (1.8) are written, and an estimate is made for the uncertain part. The result is 1.86 cm. When measurements are recorded this way, the numbers representing the certain measurement plus one number representing the estimate are called **significant figures**. Thus, the first measurement of 1.9 cm contains two significant figures, and the second measurement of 1.86 cm contains three significant figures.

significant figures The numbers in a measurement that represent the certainty of the measurement, plus one number representing an estimate.

The maximum number of significant figures possible in a measurement is determined by the design of the measuring device and cannot be changed by expressing the measurement in different units. The 1.8 cm length determined earlier can also be represented in terms of meters and millimeters as follows:

$$1.8 \text{ cm} = 0.018 \text{ m} = 18 \text{ mm}$$

In this form, it appears that the length expressed as 0.018 m contains four significant figures, but this is impossible; a measurement made with a device doesn't become more certain simply by changing the unit used to express the number. Thus, the zeros are not significant figures, their only function is to locate the correct position for the decimal. Zeros located to the left of nonzero numbers, such as the two zeros in 0.018 cm, are never considered to be significant. Thus, 12.5 mg, 0.0125 g, and 0.0000125 kg all represent the same measured mass, and all contain three significant figures.

Zeros located between nonzero numbers are considered significant. Thus, 2055 μL, 2.055 mL, and 0.002055 L all represent the same volume measurement, and all contain four significant figures. Trailing zeros at the end of a number are significant if there is a decimal point present in the number. Otherwise, trailing zeros are not significant (see **Figure 1.20**).

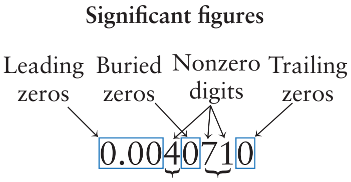


FIGURE 1.20 Five significant figures.

The rule that covers trailing zeros is generally followed by scientists, but sometimes there is ambiguity. For example, suppose you read in a newspaper that the population of a city is 1,250,000 people. Should the four trailing zeros be considered significant? If they are, it means that the population is known with certainty to the nearest 10 people and that the measurement has an uncertainty of only plus or minus 1 person. A more reasonable conclusion is that the census is correct to the nearest 1000 people. This could be represented using scientific notation, 1.250×10^6. In this case, only four significant figures are used. In scientific notation, the correct number of significant figures is used in the nonexponential term, and the location of the decimal is determined by the exponent. In this book, large numbers will always be represented by scientific notation. However, you are likely to encounter nonsignificant trailing zeros in other reading materials. The rules for determining the significance of zeros are summarized as follows:

1. Zeros not preceded by nonzero numbers are not significant figures. These zeros are sometimes called *leading zeros.*
2. Zeros located between nonzero numbers are significant figures. These zeros are sometimes called *buried* or *confined zeros.*
3. Zeros located at the end of a number are significant figures if there is a decimal point present in the number. These zeros are sometimes called *trailing zeros.* If no decimal point is present, trailing zeros are not significant.

Example 1.12 Significant Figures and Scientific Notation

Determine the number of significant figures in each of the following measurements, and use scientific notation to express each measurement using the correct number of significant figures:

a. 24.6°C b. 0.036 g c. 15.0 mL d. 0.0020 m

Solution

a. All the numbers are significant: three significant figures, 2.46×10^1 °C.
b. The leading zeros are not significant: two significant figures, 3.6×10^{-2} g.
c. The trailing zero is significant: three significant figures, 1.50×10^1 mL.
d. The leading zeros are not significant, but the trailing zero is: two significant figures, 2.0×10^{-3} m.

✔ **LEARNING CHECK 1.11** Determine the number of significant figures in each of the following measurements:

a. 250 mg
b. 18.05 mL
c. 0.0108 kg
d. 37°C
e. 0.001 mm
f. 101.0 K

✔ **LEARNING CHECK 1.12** Use scientific notation to express each of the following measurements using the correct number of significant figures:

a. 101 m
b. 1200 g
c. 0.00230 kg
d. 1296°C
e. 21.65 mL
f. 0.015 km

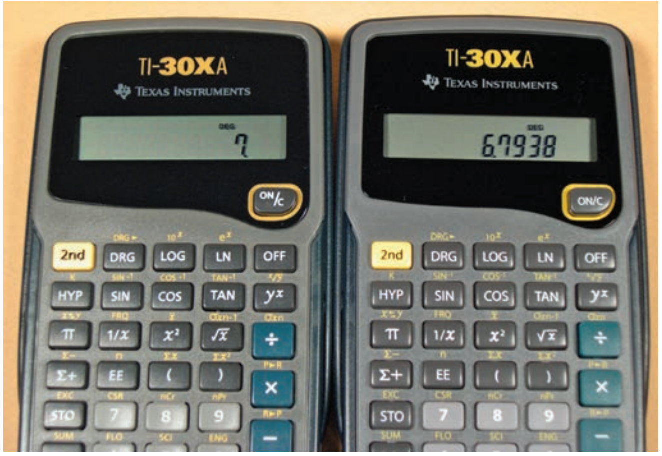
Most measurements that are made do not stand as final answers. Instead, they are usually used to make calculations involving multiplication, division, addition, or subtraction. The answer obtained from such a calculation cannot have more certainty than the least certain measurement used in the calculation. It should be written to reflect an uncertainty equal to that of the most uncertain measurement. This is accomplished by the following rules:

1. The answer obtained by multiplication or division must contain the same number of significant figures as the quantity with the fewest significant figures used in the calculation.
2. The answer obtained by addition or subtraction must contain the same number of places to the right of the decimal as the quantity in the calculation with the fewest number of places to the right of the decimal.

To follow these rules, it is often necessary to reduce the number of significant figures by rounding answers. The following are rules for rounding:

1. If the first of the nonsignificant figures to be dropped from an answer is 5 or greater, all the nonsignificant figures are dropped, and the last significant figure is increased by 1.
2. If the first of the nonsignificant figures to be dropped from an answer is less than 5, all nonsignificant figures are dropped, and the last significant figure is left unchanged.

Remember, if you use a calculator, it will often express answers with too few or too many figures (see **Figure 1.21**). It will be up to you to determine the proper number of significant figures to use and to round the calculator answer correctly.



© Jeffrey M. Seager

FIGURE 1.21 Calculators usually display the sum of 4.362 and 2.638 as 7 (too few figures), and the product of 0.67 and 10.14 as 6.7938 (too many figures).

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 1.13 Significant Figures in Multiplication and Division

On a typical day, nurses make numerous measurements and calculations. Reporting data in the most meaningful way is critical. Do the following calculations, and round the answers to the correct number of significant figures:

a. $(4.95)(12.10)$ b. $\dfrac{3.0954}{0.0085}$ c. $\dfrac{(9.15)(0.9100)}{3.117}$ d. $\dfrac{320}{4.00}$

Solution

All calculations are done with a calculator, and the calculator answer is written first. Appropriate rounding is done to get the final answer.

a. Calculator answer: 59.895
The number 4.95 has three significant figures, and 12.10 has four. Thus, the answer must have three significant figures:

$$\underbrace{59.8}_{\substack{\text{significant}\\ \text{figures}}}\underbrace{95}_{\substack{\text{nonsignificant}\\ \text{figures}}}$$

The first of the nonsignificant figures to be dropped is 9, so after both are dropped, the last significant figure is increased by 1. The final answer containing three significant figures is 59.9.

b. Calculator answer: 364.16471
The number 3.0954 has five significant figures, and 0.0085 has two. Thus, the answer must have only two:

$$\underbrace{36}_{\substack{\text{significant}\\ \text{figures}}}\underbrace{4.16471}_{\substack{\text{nonsignificant}\\ \text{figures}}}$$

The first of the nonsignificant figures to be dropped is 4, so the last significant figure remains unchanged after the nonsignificant figures are dropped. The correct answer then is 360, which contains two significant figures. The answer also can be written with the proper number of significant figures by using scientific notation, 3.6×10^2.

c. Calculator answer: 2.6713186
The number 9.15 has three significant figures, 0.9100 has four, and 3.117 has four. Thus, the answer must have only three:

$$\underbrace{2.67}_{\substack{\text{significant}\\ \text{figures}}}\underbrace{13186}_{\substack{\text{nonsignificant}\\ \text{figures}}}$$

Appropriate rounding gives 2.67 as the correct answer.

d. Calculator answer: 80
The number 320 has two significant figures and 4.00 contains three significant figures, so the answer should have two. The correct answer should be expressed as 80.0, which contains two significant figures.

✔ **LEARNING CHECK 1.13** Do the following calculations, and round the answers to the correct number of significant figures:

a. $(0.0019)(21.39)$ b. $\dfrac{8.321}{4.1}$ c. $\dfrac{(0.0911)(3.22)}{1.379}$

Example 1.14 Significant Figures in Addition and Subtraction

Do the following additions and subtractions, and write the answers with the correct number of significant figures:

a. 1.9 + 18.65 b. 15.00 − 8.0 c. 1500 + 10.9 + 0.005 d. 5.1196 − 5.02

Solution

In each case, the numbers are arranged vertically with the decimals in a vertical line. The answer is then rounded so it contains the same number of places to the right of the decimal as the smallest number of places in the quantities added or subtracted.

a.
$$\begin{array}{r} 1.9 \\ 18.65 \\ \hline 20.55 \end{array}$$

The answer must be expressed with one place to the right of the decimal to match the one place in 1.9.

Correct answer: 20.6 (Why was the final 5 increased to 6?)

b.
$$\begin{array}{r} 15.00 \\ -8.0 \\ \hline 7.0 \end{array}$$

The answer must be expressed using one place to the right of the decimal to match the 8.0. A typical calculator answer would probably be 7, requiring that a zero be added to the right of the decimal to provide the correct number of significant figures.

c.
$$\begin{array}{r} 1500. \\ 10.9 \\ 0.005 \\ \hline 1510.905 \end{array}$$

The answer must be expressed with no places to the right of the decimal to match the 1500.

Correct answer: 1511 (Why was the final 0 of the answer increased to 1?)

d.
$$\begin{array}{r} 5.1196 \\ -5.02 \\ \hline 0.0996 \end{array}$$

The answer must be expressed with two places to the right of the decimal to match the 5.02.

Correct answer: 0.10 (Which rounding rule was followed?)

Notice that the answer to (a) has more significant figures than the least significant number used in the calculation. The answer to (d), on the other hand, has fewer significant figures than either number used in the calculation. This happened because the rule for dealing with addition and subtraction focuses on the number of figures located to the right of the decimal and is not concerned with the figures to the left of the decimal. Thus, the number of significant figures in the answer is sometimes increased as a result of addition and decreased as a result of subtraction. You should be aware of this and not be confused when ever it happens.

✔ **LEARNING CHECK 1.14** Do the following additions and subtractions, and round the answers to the correct number of significant figures:

a. 8.01 + 3.2
b. 3000 + 20.3 + 0.009
c. 4.33 − 3.12
d. 6.023 − 2.42

Some numbers used in calculations are **exact numbers** that have no uncertainty associated with them and are considered to contain an unlimited number of significant trailing zeros. Such numbers are not used when the appropriate number of significant figures is determined for calculated answers. In other words, exact numbers do not limit the number of significant figures in calculated answers. One kind of exact number is a number used as part of a defined relationship between quantities. For example, 1 m contains exactly 100 cm:

$$1 \text{ m} = 100 \text{ cm}$$

Thus, the numbers 1 and 100 are exact. A second kind of exact number is a counting number obtained by counting individual objects. A dozen eggs contains exactly 12 eggs, not

exact numbers Numbers that have no uncertainty; numbers from defined relationships, counting numbers, and numbers that are part of simple fractions.

11.8 and not 12.3. The 12 is an exact counting number. A third kind of exact number is one that is part of a simple fraction such as $\frac{1}{4}$, $\frac{2}{3}$, or $\frac{5}{9}$ used in Equation 1.1 to convert Fahrenheit temperature readings into Celsius readings.

1.9 Using Units in Calculations

Learning Objective 9 Use the factor-unit method to solve numerical problems.

Some beginning chemistry students are concerned about not being able to solve numerical chemistry problems. They may say, "I can work the problems, I just can't set them up." What they are really saying is "I can do the arithmetic once the numbers are properly arranged, but I can't do the arranging."

This section presents a method for arranging numbers that will work for most of the numerical problems you will encounter in this course. This method has a number of names, including the factor-unit method, the factor-label method, and dimensional analysis. We will call it the factor-unit method. It is a systematic approach to solve numerical problems and consists of the following steps:

STEP 1 Write down the known or given quantity. Include both the numerical value and units of the quantity.

STEP 2 Leave some working space and set the known quantity equal to the units of the unknown quantity.

STEP 3 Multiply the known quantity by one or more factors, such that the units of the factor cancel the units of the known quantity and generate the units of the unknown quantity. These **factors** are fractions derived from numerical relationships between quantities. These relationships can be definitions or experimentally measured quantities. For example, the defined relationship 1 m = 100 cm provides the following two factors:

factors used in the factor-unit method Fractions obtained from numerical relationships between quantities.

$$\frac{1\ \text{m}}{100\ \text{cm}} \quad \text{and} \quad \frac{100\ \text{cm}}{1\ \text{m}}$$

STEP 4 After you get the desired units, do the necessary arithmetic to produce the final answer.

Example 1.15 Factor-Unit Calculations

As part of an annual physical exam, Brent's weight was recorded as 145 lb. What would Brent's weight be in kilograms? Use the factor-unit method and numerical relationships from **Table 1.3**.

Solution

The known quantity is 145 lb, and the unit of the unknown quantity is kilograms (kg).

STEP 1 145 lb

STEP 2 145 lb = ___ kg

STEP 3 $145\ \cancel{\text{lb}} \times \frac{1\ \text{kg}}{2.20\ \cancel{\text{lb}}} = \quad \text{kg}$

The factor $\frac{1\ \text{kg}}{2.20\ \text{lb}}$ came from the numerical relationship

1 kg = 2.20 lb found in **Table 1.3**.

STEP 4 $\frac{(145)(1)\ \text{kg}}{2.20} = 65.9090\ \text{kg} = 65.9\ \text{kg}$

STEP 5 Check to see whether the answer makes sense.

Yes. The answer should be rounded to 65.9 kg, an answer that contains three significant figures, just as 145 lb does. The 1 kg in the factor is an exact number used as part of a defined relationship, so it doesn't influence the number of significant figures in the answer.

Example 1.16 More Factor-Unit Calculations

A clinical technician uses a micropipet to measure a 5.0 μL (5.0 microliter) sample of blood serum for analysis. Express the sample volume in liters (L).

Solution

The known quantity is 5.0 μL, and the unit of the unknown quantity is liters.

STEP 1 $5.0\ \mu\text{L}$

STEP 2 $5.0\ \mu\text{L} \times \underline{\hspace{3cm}} = \text{L}$

STEP 3 $5.0\ \cancel{\mu\text{L}} \times \dfrac{1 \times 10^{-6}\ \text{L}}{1\ \cancel{\mu\text{L}}} = \text{L}$

The factor $\dfrac{1 \times 10^{-6}\ \text{L}}{1\ \mu\text{L}}$ came from the numerical relationship $1\ \mu\text{L} = 1 \times 10^{-6}\ \text{L}$ described in **Table 1.2**.

STEP 4 $\dfrac{(5.0)(1 \times 10^{-6}\ \text{L})}{1} = 5.0 \times 10^{-6}\ \text{L}$

The answer is expressed using the same number of significant figures as the 5.0 μL because 1 and 1×10^{-6} are exact numbers by definition.

STEP 5 Check to see whether your answer makes sense.

Yes. The unit is correct and the number seems reasonable.

> ✔ **LEARNING CHECK 1.15** Creatinine is a substance found in the blood. An analysis of a blood serum sample detected 1.1 mg of creatinine. Express this amount in grams by using the factor-unit method. Remember, the prefix milli- means $\frac{1}{1000}$, so 1 g = 1000 mg.

Example 1.17 More Factor-Unit Calculations

One of the fastest-moving nerve impulses in the body travels at a speed of 405 feet per second (ft/s). What is the speed in miles per hour?

Solution

The known quantity is 405 ft/s, and the unit of the unknown quantity is miles per hour (mi/h).

STEP 1 $\dfrac{405\ \text{ft}}{\text{s}}$

STEP 2 $\dfrac{405\ \text{ft}}{\text{s}} \qquad\qquad = \dfrac{\text{mi}}{\text{h}}$

STEP 3 $\left(\dfrac{405\ \cancel{\text{ft}}}{\cancel{\text{s}}}\right)\left(\dfrac{1\ \text{mi}}{5280\ \cancel{\text{ft}}}\right)\left(\dfrac{60\ \cancel{\text{s}}}{1\ \cancel{\text{min}}}\right)\left(\dfrac{60\ \cancel{\text{min}}}{1\ \text{h}}\right) = \dfrac{\text{mi}}{\text{h}}$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The factors came from the following well-known numerical relationships: 1 mi = 5280 ft, 1 min = 60 s, 1 h = 60 min. All numbers in these factors are exact numbers based on definitions.

STEP 4 $$\frac{(405)(1)(60)(60)\text{ mi}}{(5280)(1)(1)\text{ h}} = 276.1\ \frac{\text{mi}}{\text{h}}$$

Rounding to three significant figures, the same as in 405 ft/s, gives 276 mi/h.

STEP 5 Check to see whether your answer makes sense.
Yes. The unit is correct and the number seems reasonable.

> ✔ **LEARNING CHECK 1.16** A world-class sprinter can run 100 m in 10.0 s. This corresponds to a speed of 10.0 m/s. Convert this speed to miles per hour. Use information from **Table 1.3** (see page 18).

1.10 Calculating Percentages

Learning Objective 10 Do calculations involving percentages.

The word *percent* literally means per one hundred. It is the number of specific items in a group of 100 such items. Since items are seldom found in groups of exactly 100, we usually have to calculate the number of specific items that would be in the group, if it did contain exactly 100 items. This number is the percentage, and the calculation follows:

$$\text{percent} = \frac{\text{number of specific items}}{\text{total items in the group}} \times 100 \tag{1.5}$$

$$\% = \frac{\text{part}}{\text{total}} \times 100 \tag{1.6}$$

In Equation 1.6, the word *part* is used to represent the number of specific items included in the total.

Example 1.18 Percentage Calculations

On the advice of his doctor, Mark lost 21 pounds in body weight. If Mark's initial weight was 208 pounds, what percentage of his weight was lost?

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: Beginning weight = 208 pounds
Unknown: percent = ?
Weight lost = 21 pounds

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{Key Equation 1.6: } \% = \frac{\text{part}}{\text{total}} \times 100$$

STEP 3 Enter the data into the formula.

$$\% = \frac{21\text{ pounds}}{208\text{ pounds}} \times 100 = 10\%\text{ (rounded)}$$

STEP 4 Check to see whether the answer makes sense.

Yes, 10% is $\frac{1}{10}$. Mark lost about $\frac{1}{10}$ of his weight.

✔ LEARNING CHECK 1.17 In an effort to lose weight, Debra went from a beginning weight of 184 pounds to a new weight of 167 pounds. What percent of her initial weight was lost?

Rearrangement of Equation 1.6 gives another useful percent relationship. Because % = part/total × 100,

$$\text{part} = \frac{(\%)(\text{total})}{100} \qquad (1.7)$$

According to Equation 1.7, the number of specific items corresponding to a percentage can be calculated by multiplying the percentage and total, then dividing their product by 100.

Example 1.19 More Percentage Calculations

The human body is approximately 65% water by mass. What is the mass of water in a 170-pound (lb) person?

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: 65% water
Unknown: mass of water = ?
in 170 lb person

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{Key Equation 1.7: part} = \frac{(\%)(\text{total})}{100}$$

STEP 3 Enter the data into the formula.

$$\text{Part} = \frac{(65\%)(170 \text{ lb})}{100} = 110.5 \text{ lb}$$

We should round our answer to only two significant figures to match the two in the 65%. The answer is 110 lb, where the trailing zero is not significant.

STEP 4 Check to see whether the answer makes sense.

Yes, If 65% of the body is water, you would expect the weight of water to be greater than half of the body weight.

✔ LEARNING CHECK 1.18

a. A student is saving money to buy a computer that will cost a total of $1200. The student has saved $988. What percentage of the purchase price has been saved?
b. In a chemistry class of 83 students, 90.4% voted not to have the final exam. How many students wanted to have the exam?

STUDY TOOLS 1.1

Help with Calculations

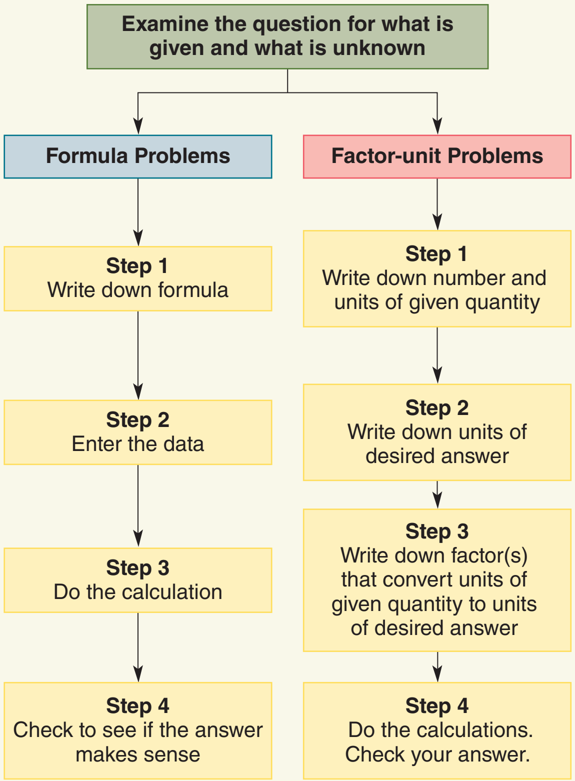
Many students feel uneasy about working chemistry problems that involve the use of mathematics. One tip that will help you solve such problems in this textbook is to remember that almost all of these problems are one of two types: those for which a specific formula applies and those where the factor-unit method is used. When you encounter a math-type problem, your first task should be to decide which type of problem it is, formula or factor-unit.

In this chapter, examples of formula-type problems are percentage calculations (see Examples 1.18 and 1.19).

In this textbook, the factor-unit method discussed in **Section 1.9** is used for many problems that require mathematical calculations. The beauty of this method is that it mimics your natural, everyday way of solving problems. This real-life method usually involves identifying where you are, where you want to go, and how to get there.

A key to working story problems is to see through all the words and find what is given (number and units). Then look for what is wanted by focusing on key words or phrases like "how much," "what is," and "calculate." Finally, use one of the two methods, formula or factor-unit, to solve the problem.

The steps to follow in solving both types of problems are summarized in the following flow charts.


Examine the question for what is given and what is unknown
Formula Problems
Factor-unit Problems
Step 1
Write down formula
Step 2
Enter the data
Step 3
Do the calculation
Step 4
Check to see if the answer makes sense
Step 1
Write down number and units of given quantity
Step 2
Write down units of desired answer
Step 3
Write down factor(s) that convert units of given quantity to units of desired answer
Step 4
Do the calculations. Check your answer.

1.11 Density

Learning Objective 11 Do calculations involving densities.

A discussion on the density of matter will conclude the topics of this chapter. Density is a physical property of matter, so it can be measured without changing the composition of the sample of matter under investigation. **Density** is the number obtained by dividing the mass of a sample of matter by the volume of the same sample.

density The number given when the mass of a sample of a substance is divided by the volume of the same sample.

$$\text{density} = \frac{\text{mass}}{\text{volume}} \tag{1.8}$$

$$d = \frac{m}{V} \tag{1.9}$$

We see from these equations that once a numerical value has been obtained for the density, two factors are available that relate mass and volume, and these may be used to solve problems.

Example 1.20 Using Density in Calculations

a. Low-density lipoprotein (LDL) cholesterol is often referred to as the "bad" cholesterol. If a blood test reveals that a 0.365-g sample of LDL had a volume of 0.353 mL, what is the density of the LDL sample in g/mL?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

b. The density of iron metal has been determined to be 7.20 g/cm^3. Use the density value to calculate the mass of an iron sample that has a volume of 35.0 cm^3.

Solution

a. **STEP 1** Examine the question for what is given and what is unknown.

$$\text{Given: } m = 0.365 \text{ g and } V = 0.353 \text{ mL}$$
$$\text{Unknown: } d = \text{?}$$

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{Key Equation 1.9: } d = \frac{m}{V}$$

STEP 3 Enter the data into the formula.

$$d = \frac{0.365 \text{ g}}{0.353 \text{ mL}} = 1.03 \text{ g/mL}$$

STEP 4 Check to see if the answer makes sense. Yes. The density is slightly greater than 1.

b. **STEP 1** Examine the question for what is given and what is unknown.

$$\text{Given: } d = 7.20 \text{ g/cm}^3$$
$$\text{Unknown: } m = \text{?}$$
$$V = 35.0 \text{ cm}^3$$

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{Key Equation 1.9: } d = \frac{m}{V}$$

STEP 3 Enter the data into the formula.

$$7.20 \text{ g/cm}^3 = \frac{m}{35.0 \text{ cm}^3}$$

Multiply both sides of the equation by the denominator, 35.0 cm^3

$$(7.20 \text{ g/cm}^3)(35.0 \text{ cm}^3) = \left(\frac{\text{m}}{\cancel{35.0 \text{ cm}^3}}\right)(\cancel{35.0 \text{ cm}^3})$$
$$m = 252 \text{ g}$$

STEP 4 Check to see whether the answer makes sense.

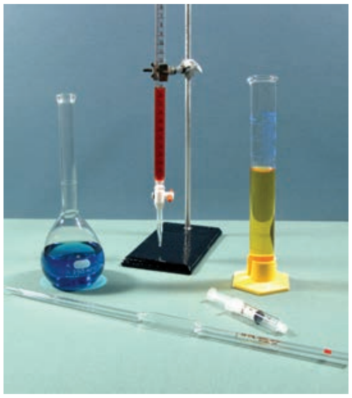
Yes. 252 divided by 35 would give about 7 for the density.

✔ LEARNING CHECK 1.19

a. A patient receives a transfusion 1.20 L of type O blood. If the density of the blood is 1.04 g/mL, how many grams of blood did the patient receive?

b. Aluminum metal has a density of 2.7 g/cm^3. Calculate the volume of an aluminum sample that has a mass of 98.5 g.

For some substances, density is rather easily determined experimentally by direct measurement. The mass of a sample is obtained by weighing the sample. The sample volume can be calculated if the sample is a regular solid such as a cube. If the sample is a liquid or an irregular solid, the volume can be measured by using volumetric apparatus such as those shown in **Figure 1.22**. Densities of solids are often given in units of g/cm^3, and those of liquids in units of g/mL because of the different ways the volumes are determined. However, according to **Table 1.3**, 1 cm^3 = 1 mL, so the numerical value is the same regardless of which of the two volume units is used.



© Jeffrey M. Seager

FIGURE 1.22 Glassware for measuring volumes of liquids. Clockwise from top center: buret, graduated cylinder, syringe, pipet, and volumetric flask.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS 1.2

Choose Wisely for Health Information

The World Wide Web contains more than three million sites that are related to health issues or health problems or that sell health products. Many of these sites are very good resources for individuals concerned about such topics. Unfortunately, however, there are also sites run by scam artists who are simply interested in trying to make money at the expense of gullible or uneducated Web surfers. The information provided by these sites is not only useless but might also be dangerous. There have been reports of sites run by individuals claiming to have a "miracle cure" for serious diseases. The sites encourage individuals to stop taking their prescription medication and instead buy the new miracle product. Another characteristic of a site to be avoided is one that claims to have a physician who will diagnose or treat you without requiring you to have a proper examination and consultation. As a general rule, you should use common sense. Another good idea is to find websites that are already linked with organizations you are familiar with or recognize as being legitimate. The following sites are very helpful and contain accurate and complete information.

National Cancer Institute: *www.cancer.gov*
Centers for Disease Control and Prevention: *www.cdc.gov*
New England Journal of Medicine: *www.nejm.org*
American Medical Association: *www.ama-assn.org/*
American Cancer Society: *www.cancer.org*
Harvard Health Publications: *www.health.harvard.edu*
Mayo Clinic: *www.mayoclinic.org*

iStockphoto.com/Daniel Laflor

An enormous amount of health information is available through home computers and the Internet.

Example 1.21 More Use of Density in Calculations

a. A hypodermic syringe was used to deliver 5.0 cc (cm^3) of alcohol into an empty container that had a mass of 25.12 g when empty. The container with the alcohol sample weighed 29.08 g. Calculate the density of the alcohol.

b. A cube of copper metal measures 2.00 cm on each edge and weighs 71.36 g. What is the density of the copper sample?

Solution

a. **STEP 1** Examine the question for what is given and what is unknown.

$$\text{Given: } V = 5.0 \text{ cc}$$
$$\text{Unknown: } d = ?$$
$$m = 25.12 \text{ g (empty)}$$
$$m = 29.08 \text{ g (full)}$$

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{Key Equation 1.9: } d = \frac{m}{V}$$

STEP 3 Enter the data into the formula.

According to **Table 1.3**, 1 cc (or cm^3) = 1 mL, so the volume is 5.0 mL. The sample mass is equal to the difference between the mass of the container with the sample inside and the mass of the empty container.

$$m = 29.08 \text{ g} - 25.12 \text{ g} = 3.96 \text{ g}$$
$$d = \frac{m}{V} = \frac{3.96 \text{ g}}{5.0 \text{ mL}} = 0.79 \text{ g/mL (rounded value)}$$

STEP 4 Check to see whether the answer makes sense.

Yes. About 4 divided by 5, would give a density of about 0.8.

b. **STEP 1** Examine the question for what is given and what is unknown.

$$\text{Given: cube 2.00 cm each side}$$
$$\text{Unknown: } d = ?$$
$$\text{mass} = 71.36 \text{ g}$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STEP 2 Identify a formula that links the give and the unknown terms.

$$\text{Key Equation 1.9: } d = \frac{m}{V}$$

STEP 3 Enter the data into the formula.

The volume of a cube is equal to the product of the three sides:

$$V = (2.00 \text{ cm})(2.00 \text{ cm})(2.00 \text{ cm}) = 8.00 \text{ cm}^3$$

$$d = \frac{m}{V} = \frac{71.36 \text{ g}}{8.00 \text{ cm}^3} = 8.92 \text{ g/cm}^3 \text{ (rounded value)}$$

STEP 4 Check to see whether the answer makes sense.

Yes. About 70 divided by 8, would give a density value of about 9.

✓ LEARNING CHECK 1.20

a. A pipet was used to put a 10.00 mL sample of a liquid into an empty container. The empty container weighed 51.22 g, and the container with the liquid sample weighed 64.93 g. Calculate the density of the liquid in g/mL.

b. A box of small irregular pieces of metal was found in a storage room. It was known that the metal was either nickel or chromium. A 35.66 g sample of the metal was weighed and put into a graduated cylinder that contained 21.2 mL of water (**Figure 1.23**). The water level after the metal was added was 25.2 mL (**Figure 1.23**, right). Was the metal nickel (density = 8.9 g/cm^3) or chromium (density = 7.2 g/cm^3)?

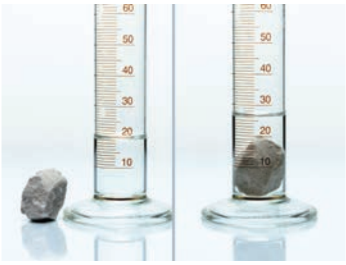

Turtle Rock Scientific/Science Source

FIGURE 1.23 Measuring the volume of irregular metal pieces.

Health Career Description

STERILE PROCESSING TECHNICIAN

Sterile processing technicians maintain the cleanliness and functionality of medical and surgical equipment. They may work in hospitals, surgery centers, cosmetic surgery clinics, or laboratories. Training programs are available through universities or technical colleges.

Sterile processing technicians certify that equipment destined for use in procedures and surgeries is reliably sterile and available as needed, when physicians or other professionals require equipment.

According to one sterile processing technician program, students learn to:

- sterilize instrumentation and equipment through a series of critical steps
- understand microbiology and infection control as it pertains to sterile processing and decontamination procedures
- implement infection control practices to ensure that patients avoid infections
- provide instrumentation and equipment access to doctors, nurses, and allied health professionals as required.

In order to practice as a sterile process technician, one must pass a Certified Registered Central Service Technician exam (CRCST) and complete 400 hours of hands-on experience. The CRCST exam tests applicants in the following areas:

- Cleaning, decontamination, and disinfection
- Preparation and packaging
- Sterilization process
- Patient care equipment
- Sterile storage and inventory management
- Documentation and record maintenance
- Customer relations

Sterile processing technicians work behind the scenes, but their work is indispensable in maintaining the reliability and safety of health care delivery. Understanding actions of chemical disinfectants, proper handling of chemicals, and laboratory safety protocols is important in this career. The work of these technicians stops the spread of bacterial and viral infection and ensures the safety of patients, medical personnel, and the public.

Sources: American Institute of Medical Sciences and Education (AIMS). How to become a Sterile Processing Technician. Retrieved May 2, 2020 from: https://www.aimseducation.edu/blog/how-do-i-become-a-sterile-processing-technician/ International Association of Healthcare Central Service Material Management (IAHCSMM). Certified Registered Central Service Technician (CRCST). Retrieved May 2, 2020 from: https://www.iahcsmm.org/certification-menu/crcst-certification.html Portland Community Hospital. Sterile Processing Technician. Retrieved May 2, 2020 from: https://www.youtube.com/watch?v=GAOCDMbDvRQ

Concept Summary

1.1 What Is Matter?

Learning Objective: Can you explain what matter is?

- Matter is the substance of everything.
- *Matter* is defined as anything that has mass and occupies space.
- Mass is a measurement of the amount of matter present in an object.
- Weight is a measure of the gravitational force pulling down an object.

1.2 Properties and Changes

Learning Objective: Can you explain the difference between the terms *physical* and *chemical* as applied to the properties of matter and changes in matter?

- Chemical properties are determined by attempts to change one kind of matter into another.
- Physical properties are determined without attempting such changes in composition.
- Any change in matter that is accompanied by a composition change is a chemical change.
- Physical changes take place without the occurrence of any composition changes.

1.3 A Model of Matter

Learning Objective: Can you describe matter in terms of the accepted scientific model?

- Scientific models are explanations for observed behavior.
- Results of many observations led scientists to a model for matter in which all matter is composed of tiny particles.
- In many substances, these particles are called molecules.
- Molecules represent the smallest piece of substances that are capable of stable existence.
- Molecules are made up of atoms, which represent the limit of chemical subdivision of matter.
- *Diatomic, triatomic, polyatomic, homoatomic,* and *heteroatomic* are common terms used to describe the atomic composition of molecules.

1.4 Classifying Matter

Learning Objective: Can you classify matter into the correct category of each of the following pairs: heterogeneous or homogeneous, solution or pure substance, and element or compound?

- Useful categories for classifying matter are heterogenous, homogenous, solution, pure substance, element, and compound.
- All matter is either heterogeneous or homogeneous.
- Heterogeneous matter is a mixture in which the properties and appearance are not uniform.
- Homogeneous matter is either a mixture of two or more pure substances or it is a pure substance. A mixture is called a solution.
- If it is a pure substance, it is either an element (containing atoms of only one kind) or a compound (containing two or more kinds of atoms).

1.5 Measurement Units

Learning Objective: Can you recognize the use of measurement units in everyday activities?

- All measurements are based on standard units that have been agreed on and adopted.
- The earliest measurements were based on human body dimensions.
- The changeable nature of such basic units made the adoption of a worldwide standard necessary.
- A standard system of units called the metric system was developed.

1.6 The Metric System

Learning Objective: Can you recognize units of the metric system, and can you convert measurements done using the metric system into related units?

- The metric system of measurement is used by most scientists worldwide and all major nations except the United States.
- It is a decimal system in which larger and smaller units of a quantity are related by factors of 10.
- Prefixes are used to designate relationships between the base unit and larger or smaller units of a quantity.

1.7 Large and Small Numbers

Learning Objective: Can you express numbers using scientific notation, and can you do calculations with numbers expressed in scientific notation?

- A system of scientific notation has been devised because of difficulties in working with very large or very small numbers in calculations.
- In scientific notation, numbers are represented as products of a nonexponential number and 10 raised to some power.
- The nonexponential number is always written with the decimal in the standard position (to the right of the first nonzero digit in the number).
- Numbers written in scientific notation can be manipulated in calculations by following a few rules.

1.8 Significant Figures

Learning Objective: Can you express the results of measurements and calculations using the correct number of significant figures?

- Significant figures are the numbers representing the part of the measurement that is certain, plus one number representing an estimate.
- The maximum number of significant figures possible in a measurement is determined by the design of the measuring device.
- Results of calculations made using numbers from measurements can be expressed with the proper number of significant figures by following simple rules.

1.9 Using Units in Calculations

Learning Objective: Can you use the factor-unit method to solve numerical problems?

- The factor-unit method for doing calculations is based on a specific set of steps.
- One crucial step involves the use of factors that are obtained from fixed numerical relationships between quantities.
- The units of the factor must always cancel the units of the known quantity and generate the units of the unknown or desired quantity.

1.10 Calculating Percentages

Learning Objective: Can you do calculations involving percentages?

- The word *percent* means per one hundred.
- A percentage is literally the number of specific items contained in a group of 100 items.
- Few items always occur in groups of exactly 100.
- A calculation can be done that determines how many specific items would be in a group, if the group actually did contain exactly 100 items.
- Percentage is calculated by number of specific items divided by the total items in a group, then multiplied by 100.

1.11 Density

Learning Objective: Can you do calculations involving densities?

- The density of a substance is the number obtained by dividing the mass of a sample by the volume of the same sample.
- Measured values of density provide two factors that can be used with the factor-unit method.
- These can calculate the mass of a substance if the volume is known or the volume if the mass is known.

Key Terms and Concepts

Atom (1.3)
Basic unit of measurement (1.6)
Chemical changes (1.2)
Chemical properties (1.2)
Compound (1.4)
Density (1.11)
Derived unit of measurement (1.6)
Diatomic molecules (1.3)
Element (1.4)
Exact numbers (1.8)
Factors used in the factor-unit method (1.9)
Heteroatomic molecules (1.3)
Heterogeneous matter (1.4)
Homoatomic molecules (1.3)
Homogeneous matter (1.4)
Mass (1.1)
Matter (1.1)
Mixture (1.4)
Molecule (1.3)
Physical changes (1.2)
Physical properties (1.2)
Polyatomic molecules (1.3)
Pure substance (1.4)
Scientific models (1.3)
Scientific notation (1.7)
Significant figures (1.8)
Solutions (1.4)
Standard position for a decimal (1.7)
Triatomic molecules (1.3)
Weight (1.1)

Key Equations

1. Conversion of temperature readings from one scale to another (**Section 1.6**)	$°\text{C} = \frac{5}{9}(°\text{F} - 32)$ $°\text{F} = \frac{9}{5}(°\text{C}) + 32°$ $°\text{C} = \text{K} - 273$ $\text{K} = °\text{C} + 273$	Equation 1.1 Equation 1.2 Equation 1.3 Equation 1.4
2. Calculation of percentage (**Section 1.10**)	$\text{Percent} = \frac{\text{number of specific items}}{\text{total items in the group}} \times 100$ $\% = \frac{\text{part}}{\text{total}} \times 100$	Equation 1.5 Equation 1.6
3. Calculation of number of items representing a specific percentage of a total (**Section 1.10**)	$\text{Part} = \frac{(\%)(\text{total})}{100}$	Equation 1.7
4. Calculation of density from mass and volume data (**Section 1.11**)	$d = \frac{m}{V}$	Equation 1.9

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

What Is Matter? (Section 1.1)

1.1 A heavy steel ball is suspended by a thin wire. The ball is hit from the side with a hammer but hardly moves. Describe what you think would happen if this identical experiment were carried out on the moon.

1.2 Explain how the following are related to each other: matter, mass, and weight.

1.3 Tell how you would try to prove to a doubter that air is matter.

1.4 Which of the following do you think is likely to change the most when done on Earth and then on the moon? Carefully explain your reasoning.

- **a.** The distance you can throw a bowling ball.
- **b.** The distance you can roll a bowling ball on a flat, smooth surface.

1.5 The attractive force of gravity for objects near Earth's surface increases as you move toward Earth's center. Suppose you are transported from a deep mine to the top of a tall mountain.

- **a.** How would your mass be changed by the move?
- **b.** How would your weight be changed by the move?

1.6 Earth's rotation causes it to bulge at the equator. How would the weights of people of equal mass differ when one was determined at the equator and one at the North Pole? (See Exercise 1.5.)

Properties and Changes (Section 1.2)

1.7 Classify each of the following as a physical or chemical change, and give at least one observation, fact, or reason to support your answer.

- **a.** A plum ripens.
- **b.** Water boils.
- **c.** A glass window breaks.
- **d.** Food is digested.

1.8 Classify each of the following as a physical or chemical change, and give at least one observation, fact, or reason to support your answer.

- **a.** A stick is broken into two pieces.
- **b.** A candle burns.
- **c.** Rock salt is crushed by a hammer.
- **d.** Tree leaves change color in autumn.

1.9 Classify each of the following properties as physical or chemical. Explain your reasoning in each case.

- **a.** Unsaturated fats are liquid at room temperature.
- **b.** Oxygen gas binds with hemoglobin.
- **c.** The metal used in artificial hip joint implants is not corroded by body fluids.
- **d.** An antacid tablet neutralizes stomach acid.
- **e.** Melanin pigment is brown in color.

1.10 Classify each of the following properties as physical or chemical. Explain your reasoning in each case.

- **a.** Mercury metal is a liquid at room temperature.
- **b.** Sodium metal reacts vigorously with water.
- **c.** Water freezes at 0°C.
- **d.** Gold does not rust.
- **e.** Chlorophyll molecules are green in color.

A Model of Matter (Section 1.3)

1.11 A sample of liquid alcohol is frozen to a solid, then allowed to melt back to a liquid. Have the alcohol molecules been changed by the process? Explain your answer.

1.12 Acetylsalicylic acid is commonly known as aspirin. It is a white solid that melts at 136°C, and when it is heated gently, a gas is given off. After the gas evolution stops, a white solid remains that melts at a temperature different from 136°C.

- **a.** Have the aspirin molecules been changed by the process? Explain your answer.
- **b.** Is the white solid that remains after heating still aspirin? Explain your answer.
- **c.** In terms of the number of atoms contained, how do you think the size of the aspirin molecules compares with the size of the molecules of the white solid produced by this process? Explain your answer.
- **d.** Classify aspirin molecules by using the term *homoatomic* or *heteroatomic*. Explain your reasoning.

1.13 A sample of solid elemental phosphorus that is deep red in color is burned. While the phosphorus is burning, a white smoke is produced that is actually a finely divided solid that is collected.

- **a.** Have the molecules of phosphorus been changed by the process of burning? Explain your answer.
- **b.** Is the collected white solid a different substance from the phosphorus? Explain your answer.
- **c.** In terms of the number of atoms contained, how do you think the size of the molecules of the white solid compares with the size of the molecules of phosphorus? Explain your answer.
- **d.** Classify molecules of the collected white solid using the term *homoatomic* or *heteroatomic*. Explain your reasoning.

1.14 Oxygen gas and solid carbon are both made up of homoatomic molecules. The two react to form a single substance, carbon dioxide. Use the term *homoatomic* or *heteroatomic* to classify molecules of carbon dioxide. Explain your reasoning.

1.15 Under appropriate conditions, hydrogen peroxide can be changed to water and oxygen gas. Use the term *homoatomic* or *heteroatomic* to classify molecules of hydrogen peroxide. Explain your reasoning.

1.16 Water can be decomposed to hydrogen gas and oxygen gas by passing electricity through it. Use the term *homoatomic* or *heteroatomic* to classify molecules of water. Explain your reasoning.

1.17 Glucose, commonly known as blood sugar, is chemically broken down in the process of cellular respiration, which requires oxygen. The only products of the process are water and carbon dioxide. Use the term *homoatomic* or *heteroatomic* to classify molecules of glucose. Explain your reasoning.

Classifying Matter (Section 1.4)

1.18 Classify each pure substance represented below by a capital letter as an element or a compound. Indicate when such a classification cannot be made, and explain why.

- **a.** Substance A is composed of heteroatomic molecules.
- **b.** Substance D is composed of homoatomic molecules.
- **c.** Substance E is changed into substances G and J when it is heated.

1.19 Classify each pure substance represented below by a capital letter as an element or a compound. Indicate when such a classification cannot be made, and explain why.

- **a.** Two elements when mixed combine to form only substance L.
- **b.** An element and a compound when mixed form substances M and Q.
- **c.** Substance X is not changed by heating it.

1.20 Consider the following experiments, and answer the questions pertaining to classification:

- **a.** A pure substance R is heated, cooled, put under pressure, and exposed to light but does not change into anything else. What can be said about classifying substance R as an element or a compound? Explain your reasoning.
- **b.** Upon heating, solid pure substance T gives off a gas and leaves another solid behind. What can be said about classifying substance T as an element or compound? Explain your reasoning.
- **c.** What can be said about classifying the solid left in part b as an element or compound? Explain your reasoning.

1.21 Early scientists incorrectly classified calcium oxide (lime) as an element for a number of years. Discuss one or more reasons why you think they might have done this.

1.22 Classify each of the following as homogeneous or heterogeneous:

- **a.** blood
- **b.** liquid eye drops
- **c.** an aspirin tablet
- **d.** a urine sample with kidney stones
- **e.** intravenous saline
- **f.** an antibiotic ointment
- **g.** curdled milk

1.23 Classify each of the following as homogeneous or heterogeneous:

- **a.** muddy flood water
- **b.** gelatin dessert
- **c.** normal urine
- **d.** smog-filled air
- **e.** an apple
- **f.** mouthwash
- **g.** petroleum jelly

1.24 Classify as pure substance or solution each of the materials of Exercise 1.22 that you classified as homogeneous.

1.25 Classify as pure substance or solution each of the materials of Exercise 1.23 that you classified as homogeneous.

Measurement Units (Section 1.5)

1.26 Briefly discuss why a system of measurement units is an important part of our modern society.

1.27 In the distant past, 1 in. was defined as the length resulting from laying a specific number of grain kernels such as corn in a row. Discuss the disadvantages of such a system.

1.28 An old British unit used to express weight is a stone. It is equal to 14 lb. What sort of weighings might be expressed in stones? Suggest some standard that might have been used to establish the unit.

The Metric System (Section 1.6)

1.29 Which of the following quantities are expressed in metric units?

- **a.** The amount of aspirin in a tablet: 5 grains
- **b.** Approximate blood volume of an adult human: 5 L
- **c.** Approximate length of a human small intestine: 20 ft
- **d.** The time for a race: 4 min, 5.2 s
- **e.** Human body surface area: 1.9 m^2
- **f.** The temperature of someone having fever: 103°F

1.30 Which of the following quantities are expressed in metric units?

- **a.** Normal body temperature: 37°C
- **b.** The amount of soft drink in a bottle: 2 L
- **c.** The height of a ceiling in a room: 8.0 ft
- **d.** The amount of aspirin in a tablet: 81 mg
- **e.** The volume of a cooking pot: 4 qt
- **f.** The time for a short race to be won: 10.2 s

1.31 Referring to **Table 1.3**, suggest an appropriate metric system unit for each nonmetric unit in Exercise 1.29.

1.32 Referring to **Table 1.3**, suggest an appropriate metric system unit for each nonmetric unit in Exercise 1.30.

1.33 Referring only to **Table 1.2**, answer the following questions:

- **a.** A computer has 12 megabytes of memory storage. How many bytes of storage is this?
- **b.** A 10 km race is 6.2 mi long. How many meters long is it?
- **c.** A chemical balance can detect a mass as small as 0.1 mg. What is this detection limit in grams?
- **d.** A micrometer is a device used to measure small lengths. If it lives up to its name, what is the smallest metric length that could be measured using a micrometer?

1.34 Referring only to **Table 1.2**, answer the following questions:

- **a.** Devices are available that allow liquid volumes as small as one microliter (μL) to be measured. How many microliters would be contained in 1.00 liter?
- **b.** Electrical power is often measured in kilowatts. How many watts would equal 75 kilowatts?
- **c.** Ultrasound is sound of such high frequency that it cannot be heard. The frequency is measured in hertz

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

(vibrations per second). How many hertz correspond to 15 megahertz?

d. A chlorine atom has a diameter of 200 picometers. How many meters is this diameter?

1.35 One inch is approximately equal to 2.54 cm. Express this length in millimeters and meters.

1.36 Cookbooks are going metric. In such books, 1 cup is equal to 240 mL. Express 1 cup in terms of liters and cubic centimeters.

1.37 Two cities in Germany are located 25 km apart. What is the distance in miles?

1.38 The shotput used by female track and field athletes has a mass of 4.0 kg. What would be the weight of such a shotput in pounds?

1.39 Referring to **Table 1.3**, answer the following questions:

a. Which is longer, a centimeter or an inch of surgical tape?

b. How many milliliters are in a quart of blood?

c. How many grams are in an ounce of fat?

1.40 Referring to **Table 1.3**, answer the following questions:

a. Approximately how many inches longer is a meter stick than a yardstick?

b. A temperature increases by 65°C. How many kelvins would this increase be?

c. You have a 5 lb bag of sugar. Approximately how many kilograms of sugar do you have?

1.41* Do the following, using appropriate values from **Table 1.3**:

a. Calculate the area in square meters of a circular skating rink that has a 12.5-m radius. For a circle, the area (A) is related to the radius (r) by $A = \pi r^2$, where $\pi = 3.14$.

b. Calculate the floor area and volume of a rectangular room that is 5.0 m long, 2.8 m wide, and 2.1 m high. Express your answers in square meters and cubic meters (meters cubed).

c. A model sailboat has a triangular sail that is 25 cm high (h) and has a base (b) of 15 cm. Calculate the area (A) of the sail in square centimeters. $A = \dfrac{(b)(h)}{2}$ for a triangle.

1.42* Using appropriate values from **Table 1.3**, answer the following questions:

a. One kilogram of water has a volume of 1.0 cm^3. What is the mass of 1.0 cm^3 of water?

b. One quart is 32 fl oz. How many fluid ounces are contained in 2.0 L of saline solution?

c. Approximately how many milligrams of aspirin are contained in a 5-grain tablet?

1.43 The weather report says the temperature is 23°F. What is this temperature on the Celsius scale? On the Kelvin scale?

1.44 Recall from Health Connections 1.1 (see page 19) that a normal body temperature might be as low as 36.1°C in the morning and as high as 37.2°C at bedtime. What are these temperatures on the Fahrenheit scale?

1.45 One pound of body fat releases approximately 4500 kcal of energy when it is metabolized. How many joules of energy is this? How many BTUs?

Large and Small Numbers (Section 1.7)

1.46 Which of the following numbers are written using scientific notation correctly? For those that are not, explain what is wrong.

a. 02.7×10^{-3}

b. 4.1×10^{2}

c. 71.9×10^{-6}

d. 10^{3}

e. $.0405 \times 10^{-2}$

f. 0.119

1.47 Which of the following numbers are written using scientific notation correctly? For those that are not, explain what is wrong.

a. 4.2×10^{3}

b. 6.8^{4}

c. 202×10^{-3}

d. 0.026×10^{-2}

e. 10^{-2}

f. 74.5×10^{5}

1.48 Write each of the following numbers using scientific notation.

a. 14 thousand

b. 365

c. 0.00204

d. 461.8

e. 0.00100

f. 9.11 hundred

1.49 Write each of the following numbers using scientific notation.

a. three hundred

b. 4003

c. 0.682

d. 91.86

e. six thousand

f. 400

1.50 The speed of light is about 186 thousand mi/s, or 1100 million km/h. Write both numbers using scientific notation.

1.51 A human hair has a diameter of 0.0651 mm, or 0.00256 inches. Write both numbers using scientific notation.

1.52 A single copper atom has a mass of 1.05×10^{-22} g. Write this number in a decimal form without using scientific notation.

1.53 In 2.0 g of hydrogen gas, there are approximately 6.02×10^{23} hydrogen molecules. Write this number without using scientific notation.

1.54 Do the following multiplications, and express each answer using scientific notation:

a. $(8.2 \times 10^{-3})(1.1 \times 10^{-2})$

b. $(2.7 \times 10^{2})(5.1 \times 10^{4})$

c. $(3.3 \times 10^{-4})(2.3 \times 10^{2})$

d. $(9.2 \times 10^{-4})(2.1 \times 10^{4})$

e. $(4.3 \times 10^{6})(6.1 \times 10^{5})$

1.55 Do the following multiplications, and express each answer using scientific notation.

a. $(6.3 \times 10^{5})(4.2 \times 10^{-8})$

b. $(2.8 \times 10^{-3})(1.4 \times 10^{-4})$

c. $(8.6 \times 10^{2})(6.4 \times 10^{-3})$

d. $(9.1 \times 10^{4})(1.4 \times 10^{3})$

e. $(3.7 \times 10^{5})(6.1 \times 10^{-3})$

1.56 Express each of the following numbers using scientific notation, then carry out the multiplication. Express each answer using scientific notation.

a. (144)(0.0876)

b. (751)(106)

c. (0.0422)(0.00119)

d. (128,000)(0.0000316)

1.57 Express each of the following numbers using scientific notation, then carry out the multiplication. Express each answer using scientific notation.

a. (538)(0.154)

b. (600)(524)

c. (22.8)(341)

d. (23.6)(0.047)

1.58 Do the following divisions, and express each answer using scientific notation.

a. $\dfrac{3.1 \times 10^{-3}}{1.2 \times 10^{2}}$

b. $\dfrac{7.9 \times 10^{4}}{3.6 \times 10^{2}}$

c. $\dfrac{4.7 \times 10^{-1}}{7.4 \times 10^{2}}$

d. $\dfrac{0.00229}{3.16}$

e. $\dfrac{119}{3.8 \times 10^{3}}$

1.59 Do the following divisions, and express each answer using scientific notation.

a. $\dfrac{223}{1.67}$

b. $\dfrac{6.7 \times 10^{3}}{4.2 \times 10^{4}}$

c. $\dfrac{8.7 \times 10^{-4}}{2.3 \times 10^{-2}}$

d. $\dfrac{6.8 \times 10^{3}}{2.7 \times 10^{-4}}$

e. $\dfrac{1.8 \times 10^{-2}}{6.5 \times 10^{4}}$

1.60 Do the following calculations, and express each answer using scientific notation.

a. $\dfrac{(5.3)(0.22)}{(6.1)(1.1)}$

b. $\dfrac{(3.8 \times 10^{-4})(1.7 \times 10^{-2})}{6.3 \times 10^{3}}$

c. $\dfrac{4.8 \times 10^{6}}{(7.4 \times 10^{3})(2.5 \times 10^{-4})}$

d. $\dfrac{5.6}{(0.022)(109)}$

e. $\dfrac{(4.6 \times 10^{-3})(2.3 \times 10^{2})}{(7.4 \times 10^{-4})(9.4 \times 10^{-5})}$

1.61 Do the following calculations, and express each answer using scientific notation.

a. $\dfrac{(7.4 \times 10^{-3})(1.3 \times 10^{4})}{5.5 \times 10^{-2}}$

b. $\dfrac{6.4 \times 10^{5}}{(8.8 \times 10^{3})(1.9 \times 10^{-4})}$

c. $\dfrac{(6.4 \times 10^{-2})(1.1 \times 10^{-8})}{(2.7 \times 10^{-4})(3.4 \times 10^{-4})}$

d. $\dfrac{(963)(1.03)}{(0.555)(412)}$

e. $\dfrac{1.15}{(0.12)(0.73)}$

Significant Figures (Section 1.8)

1.62 Indicate to what decimal position readings should be estimated and recorded (nearest 0.1, 0.01, etc.) for measurements made with the following devices:

a. A ruler with a smallest scale marking of 0.1 cm

b. A measuring telescope with a smallest scale marking of 0.1 mm

c. A protractor with a smallest scale marking of 1°

d. A tire pressure gauge with a smallest scale marking of 1 lb/in^{2}.

1.63 Indicate to what decimal position readings should be estimated and recorded (nearest 0.1, 0.01, etc.) for measurements made with the following devices:

a. A buret with a smallest scale marking of 0.1 mL

b. A graduated cylinder with a smallest scale marking of 1 mL

c. A thermometer with a smallest scale marking of 0.1°C

d. A barometer with a smallest scale marking of 1 torr

1.64 Write the following measured quantities as a health professional would record them, using the correct number of significant figures based on the device used to make the measurement.

a. Exactly 6 mL of water measured with a syringe whose smallest scale marking is 1 mL.

b. A temperature that appears to be exactly 37°C using a thermometer with a smallest scale marking of 0.1°C.

c. A time of exactly 9 s measured with a stopwatch whose smallest scale marking is 0.1 s.

d. Fifteen and one-half degrees measured on an X-ray machine that has 1-degree scale markings.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

1.65 Write the following measured quantities as you would record them, using the correct number of significant figures based on the device used to make the measurements.

a. A length of two and one-half centimeters measured with a measuring telescope with a smallest scale marking of 0.1 mm

b. An initial reading of exactly 0 for a burette with a smallest scale marking of 0.1 mL

c. A length of four and one-half centimeters measured with a ruler that has a smallest scale marking of 0.1 cm

d. An atmospheric pressure of exactly 690 torr measured with a barometer that has a smallest scale marking of 1 torr

1.66 In each of the following, identify the measured numbers and exact numbers. Do the indicated calculation, and write your answer using the correct number of significant figures.

a. A bag of potatoes is found to weigh 5.06 lb. The bag contains 16 potatoes. Calculate the weight of an average potato.

b. The foul-shooting percentages for the five starting players of a women's basketball team are 71.2%, 66.9%, 74.1%, 80.9%, and 63.6%. What is the average shooting percentage of the five players?

1.67 In each of the following, identify the measured numbers and exact numbers. Do the indicated calculations, and write your answer using the correct number of significant figures.

a. An individual has a job of counting the number of people who enter a store between 1 p.m. and 2 p.m. each day for 5 days. The counts were 19, 24, 17, 31, and 40. What was the average number of people entering the store per day for the 5 day period?

b. The starting five members of a women's basketball team have the following heights: 6′9″, 5′8″, 5′6″, 5′1″, and 4′11″. What is the average height of the starting five?

1.68 Determine the number of significant figures in each of the following.

a. 0.0400

b. 309

c. 4.006

d. 4.4×10^{-3}

e. 1.002

f. 255.02

1.69 Determine the number of significant figures in each of the following:

a. 0.040

b. 11.91

c. 2.48×10^{2}

d. 149.1

e. 10.003

f. 148.67

1.70 Do the following calculations and use the correct number of significant figures in your answers. Assume all numbers are the results of measurements.

a. (3.71)(1.4)

b. (0.0851)(1.2262)

c. $\dfrac{(0.1432)(2.81)}{(0.7762)}$

d. $(3.3 \times 10^{4})(3.09 \times 10^{-3})$

e. $\dfrac{(760)(2.00)}{6.02 \times 10^{20}}$

1.71 Do the following calculations and use the correct number of significant figures in your answers. Assume all numbers are the results of measurements.

a. (1.21)(3.2)

b. $(6.02 \times 10^{23})(0.220)$

c. $\dfrac{(0.023)(1.1 \times 10^{-3})}{100}$

d. $\dfrac{(365)(7.000)}{60}$

e. $\dfrac{(810)(3.1)}{8.632 \times 10^{-1}}$

1.72 Do the following calculations and use the correct number of significant figures in your answers. Assume all numbers are the results of measurements.

a. 0.208 + 4.9 + 1.11

b. 228 + 0.999 + 1.02

c. 8.543 − 7.954

d. $(3.2 \times 10^{-2}) + (5.5 \times 10^{-1})$

(HINT: Write in decimal form first, then add.)

e. 336.86 − 309.11

f. 21.66 − 0.02387

1.73 Do the following calculations and use the correct number of significant figures in your answers. Assume all numbers are the results of measurements.

a. 2.1 + 5.07 + 0.119

b. 0.051 + 8.11 + 0.02

c. 4.337 − 3.211

d. $(2.93 \times 10^{-1}) + (6.2 \times 10^{-2})$

(HINT: Write in decimal form first, then add.)

e. 471.19 − 365.09

f. 17.76 − 0.0479

1.74 Do the following calculations and use the correct number of significant figures in your answers. Assume all numbers are the results of measurements. In calculations involving both addition/subtraction and multiplication/division, it is usually better to do additions/subtractions first.

a. $\dfrac{(0.0267 + 0.0019)(4.626)}{28.7794}$

b. $\dfrac{212.6 - 21.88}{86.37}$

c. $\dfrac{27.99 - 18.07}{4.63 - 0.88}$

d. $\dfrac{18.87}{2.46} - \dfrac{18.07}{0.88}$

(HINT: Do divisions first, then subtract.)

e. $\dfrac{(8.46 - 2.09)(0.51 + 0.22)}{(3.74 + 0.07)(0.16 + 0.2)}$

f. $\dfrac{12.06 - 11.84}{0.271}$

1.75 Do the following calculations and use the correct number of significant figures in your answers. Assume all numbers are the results of measurements. In calculations involving both addition/subtraction and multiplication/division, it is usually better to do additions/subtractions first.

a. $\dfrac{132.15 - 32.16}{87.55}$

b. $\dfrac{(0.0844 + 0.1021)(7.174)}{19.1101}$

c. $\dfrac{(2.78 - 0.68)(0.42 + 0.4)}{(1.058 + 0.06)(0.22 + 0.2)}$

d. $\dfrac{27.65 - 21.71}{4.97 - 0.36}$

e. $\dfrac{12.47}{6.97} - \dfrac{203.4}{201.8}$

(HINT: Do divisions first, then subtract.)

f. $\dfrac{19.37 - 18.49}{0.822}$

1.76* The following measurements were obtained for the length and width of a series of rectangles. Each measurement was made using a ruler with a smallest scale marking of 0.1 cm.

Black rectangle: $l = 12.00$ cm, $w = 10.40$ cm

Red rectangle: $l = 20.20$ cm, $w = 2.42$ cm

Green rectangle: $l = 3.18$ cm, $w = 2.55$ cm

Orange rectangle: $l = 13.22$ cm, $w = 0.68$ cm

a. Calculate the area (length × width) and perimeter (sum of all four sides) for each rectangle and express your results in square centimeters and centimeters, respectively, and give the correct number of significant figures in the result.

b. Change all measured values to meters and then calculate the area and perimeter of each rectangle. Express your answers in square meters and meters, respectively, and give the correct number of significant figures.

c. Does changing the units used change the number of significant figures in the answers?

Using Units in Calculations (Section 1.9)

1.77 It is important that health care professionals and others be able to convert English to metric units and vice versa. Determine a single factor derived from **Table 1.3** that could be used as a multiplier to make each of the following conversions.

a. 3.4 lb to kilograms

b. 3.0 yd to meters

c. 1.5 oz to grams

d. 40. cm to inches

1.78 It is important that health care professionals and others be able to convert English to metric units and vice versa. Determine a single factor derived from **Table 1.3** that could be used as a multiplier to make each of the following conversions.

a. 20 mg to grains

b. 350 mL to fl oz

c. 4 qt to liters

d. 5 yd to meters

1.79 Obtain a factor from **Table 1.3** and calculate the number of liters in 1.00 gal (4 qt) by using the factor-unit method of calculation.

1.80 A patient receives 45 mL of a drug. Obtain a factor from **Table 1.3** and use the factor-unit method to calculate how much the patient receives in fluid ounces (fl oz).

1.81 A state health department recommends that certain medications be stored between 35°F and 40°F. If the refrigerator used has a Celsius thermometer, what settings should you use?

1.82 A nurse's direction is to administer 55 mg of Garamycin (gentamicin) every 6 hr. If a vial is labeled 80 mg/2 mL, how many mL should be given?

1.83 A single tablet of baby aspirin contains 81 mg of aspirin. If someone takes 7 tablets in 1 day, how many grams of aspirin have been consumed?

1.84 If an intravenous solution is infused at the rate of 0.70 mL per minute, how many minutes will it take to administer 200 mL of solution?

1.85 A patient weighs 74.6 kg. How much is that weight in pounds?

1.86 During a glucose tolerance test, the serum glucose concentration of a patient was found to be 131 mg/dL. Convert the concentration to grams per liter.

Calculating Percentages (Section 1.10)

1.87 Retirement age is 65 years in many companies. What percentage of the way from birth to retirement is a 55 year old person?

1.88 A salesperson made a sale of $467.80 and received a commission of $25.73. What percent commission was paid?

1.89 After drying, 140 lbs of grapes yields 32 lbs of raisins. What percentage of the grapes' mass was lost during the drying process?

1.90 The recommended daily intake of thiamin is 1.4 mg for a male adult. Suppose such a person takes in only 1.0 mg/day. What percentage of the recommended intake is he receiving?

1.91 The recommended daily caloric intake for a 20-year-old woman is 2000. How many Calories should her breakfast contain if she wants it to be 45% of her recommended daily total?

1.92 Immunoglobulin antibodies occur in five forms. A sample of serum is analyzed with the following results. Calculate the percentage of total immunoglobulin represented by each type.

Type:	IgG	IgA	IgM	IgD	IgE
Amount (mg):	987.1	213.3	99.7	14.4	0.1

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Density (Section 1.11)

1.93 Calculate the density of the following materials for which the mass and volume of samples have been measured. Express the density of liquids in g/mL, the density of solids in g/cm^3, and the density of gases in g/L.

a. 250 mL of liquid mercury metal (Hg) has a mass of 3400 g.

b. 500 mL of concentrated liquid sulfuric acid (H_2SO_4) has a mass of 925 g.

c. 5.00 L of oxygen gas has a mass of 7.15 g.

d. A 200 cm^3 block of magnesium metal (Mg) has a mass of 350 g.

1.94 Calculate the density of the following materials for which the mass and volume of samples have been measured. Express the density of liquids in g/mL, the density of solids in g/cm^3, and the density of gases in g/L.

a. A 50.0 mL sample of liquid acetone has a mass of 39.6 g.

b. A 1.00-cup (236 mL) sample of homogenized milk has a mass of 243 g.

c. 20.0 L of dry carbon dioxide gas (CO_2) has a mass of 39.54 g.

d. A 25.0 cm^3 block of nickel metal (Ni) has a mass of 222.5 g.

1.95 Osteoporosis is a disease in which the density and quality of bone are reduced. If a bone sample has a volume of 1.35 cm^3 and a mass of 2.10 g, what is the density in g/cm^3?

1.96 Calculate the volume and density of a cube of lead metal (Pb) that has a mass of 718.3 g and has edges that measure 3.98 cm.

1.97* The volume of an irregularly shaped solid can be determined by immersing the solid in a liquid and measuring the volume of liquid displaced. Find the volume and density of the following:

a. An irregular piece of the mineral quartz is found to weigh 12.4 g. It is then placed into a graduated cylinder that contains some water. The quartz does not float. The water in the cylinder was at a level of 25.2 mL before the quartz was added and at 29.9 mL afterward.

b. The volume of a sample of lead shot is determined using a graduated cylinder, as in part (a). The cylinder readings are 16.3 mL before the shot is added and 21.7 mL after. The sample of shot weighs 61.0 g.

c. A sample of coarse rock salt is found to have a mass of 11.7 g. The volume of the sample is determined by the graduated-cylinder method described in (part a), but kerosene is substituted for water because the salt will not dissolve in kerosene. The cylinder readings are 20.7 mL before adding the salt and 26.1 mL after.

1.98 If the density of high-density lipoproteins (HDL) or "good cholesterol" is 1.069 g/mL, what is the volume in mL of 3.056 g of HDL?

1.99 A urine sample has a density of 1.107 g/mL. What is the mass in grams of 0.250 L of this urine?

Additional Exercises

1.100 Do the following metric system conversions by changing only the power of 10. For example, convert 2.5 L to mL: 2.5 L = 2.5×10^3 mL

a. Convert 4.5 km to mm

b. Convert 6.0×10^6 mg to g

c. Convert 9.86×10^{15} m to km

d. Convert 1.91×10^{-4} kg to mg

e. Convert 5.0 ng to mg

1.101 A single water molecule has a mass of 2.99×10^{-23} g. Each molecule contains two hydrogen atoms that together make up 11.2% of the mass of the water molecule. What is the mass in grams of a single hydrogen atom?

1.102 It has been found that fat makes up 14% of a 170 lb person's body weight. One pound of body fat provides 4500 kcal of energy when it is metabolized. The person requires 2000 kcal of energy per day to survive. Assume all the energy needed for survival comes from the metabolism of body fat, and calculate the number of days the person could survive without eating before depleting the entire body fat reserve.

1.103 Cooking oil has a density of 0.812 g/mL. What is the mass in grams of 1.00 quart of cooking oil? Use **Table 1.3** for any necessary factors.

1.104 A 175 lb patient is to undergo surgery and will be given an anesthetic intravenously. The safe dosage of anesthetic is 12 mg/kg of body weight. Determine the maximum dose of anesthetic in mg that should be used.

1.105 At 4.0°C, pure water has a density of 1.00 g/mL. At 60.0°C, the density is 0.98 g/mL. Calculate the volume in mL of 1.00 g of water at each temperature, and then calculate the percentage increase in volume that occurs as water is heated from 4.0°C to 60.0°C.

Chemistry for Thought

1.106 The following pairs of substances represent heterogeneous mixtures. For each pair, describe the steps you would follow to separate the components and collect them.

a. wood sawdust and sand

b. sugar and sand

c. iron filings and sand

d. sand soaked with oil

1.107 Explain why a bathroom mirror becomes foggy when someone takes a hot shower. Classify any changes that occur as physical or chemical.

1.108 A 20 year old student was weighed and found to have a mass of 44.5 kg. She converted this to pounds and got an answer of 20.2 lb. Describe the mistake she probably made in doing the calculation.

1.109 Liquid mercury metal freezes to a solid at a temperature of −38.9°C. Suppose you want to measure a temperature that is at least as low as −45°C. Can you use a mercury thermometer? If not, propose a way to make the measurement.

1.110 Answer the question contained in **Figure 1.5**. How does hang gliding confirm that air is an example of matter?

1.111 Show how the factor-unit method can be used to prepare an oatmeal breakfast for 27 guests at a family reunion. The directions on the oatmeal box say that 1 cup of dry oatmeal makes 3 servings.

1.112 A chemist is brought a small solid figurine. The owner wants to know if it is made of silver but doesn't want it damaged during the analysis. The chemist decides to determine the density, knowing that silver has a density of 10.5 g/mL. The figurine is put into a graduated cylinder that contains 32.6 mL of water. The reading while the figurine is in the water is 60.1 mL. The mass of the figurine is 240.8 g. Is the figurine made of silver? Explain your reasoning.

1.113 Explain what is meant by the following statement: All matter contains chemicals.

1.114 Refer to **Figure 1.9**, then use the model of matter described in **Section 1.3** to propose an explanation for the following observation. When two teaspoons of sugar are dissolved in a small glass of water, the volume of the resulting solution is not significantly larger than the original volume of the water.

2 Atoms and Molecules

Rick Loomis/Los Angeles Times/Getty Images

Environmental Career Focus

WILDLIFE TECHNICIAN

You know that cliché, "I'd rather be fishing"? Well, for me, it's true. I love picking out the perfect lure and casting it "just so" for a specific fish—you have to know what you're doing to catch a fish around here. Most of our fish are "stocked"—grown in hatcheries and transferred to the sites by trucks or even planes.

When I learned about hatcheries, I immediately wanted to work in one. I started researching jobs and found that I need at least an associate's degree in biology, and a bachelor's is even better. With this goal in mind, I was determined to gain the necessary credentials to work in a fish hatchery. Now, every day I "fish!"

To keep the fish healthy, we must sanitize our equipment, including our gloves and boots. Because we work with powerful disinfectants, like potassium peroxymonosulfate ($KHSO_5$), with delicate organisms such as fish eggs and fry, not to mention the complex ecosystems they inhabit, education is important.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Use symbols for chemical elements to write formulas for chemical compounds. **(Section 2.1)**
2. Identify the characteristics of protons, neutrons, and electrons. **(Section 2.2)**
3. Use the concepts of atomic number and mass number to determine the number of subatomic particles in isotopes and to write correct symbols for isotopes. **(Section 2.3)**
4. Use atomic weights of the elements to calculate molecular weights of compounds. **(Section 2.4)**
5. Use isotope percent abundances and masses to calculate atomic weights of elements. **(Section 2.5)**
6. Use the mole concept to obtain relationships between number of moles, number of grams, and number of atoms for elements, and use those relationships to obtain factors for use in factor-unit calculations. **(Section 2.6)**
7. Use the mole concept and molecular formulas to obtain relationships between number of moles, number of grams, and number of atoms or molecules for compounds, and use those relationships to obtain factors for use in factor-unit calculations. **(Section 2.7)**

WE INTRODUCED SOME FUNDAMENTAL ideas about matter, atoms, molecules, measurements, and calculations in Chapter 1. In this chapter, these ideas are applied, the mole is defined, and the quantitative nature of chemistry becomes more apparent. A system of symbols is introduced that simplifies the way atoms and molecules are represented.

2.1 Symbols and Formulas

Learning Objective 1 Use symbols for chemical elements to write formulas for chemical compounds.

In Chapter 1, we defined elements as homogeneous pure substances made up of identical atoms. At least 118 different elements are known to exist. This leads to the conclusion that a minimum of 118 different kinds of atoms exist. Eighty-eight of the elements are naturally occurring and therefore are found in Earth's crust, oceans, or atmosphere. The others are synthetic elements produced in the laboratory. **Figure 2.1** lists elements found within the human body.

Each element can be characterized and identified by its unique set of physical and chemical properties, but it would be very cumbersome to list all these properties each time a specific element is discussed. For this reason, each element has been assigned a unique name and symbol. Many elements have been named by their discoverer, and as a result the names are varied. Some are based on elemental properties, others came from the names of famous scientists or places, while others are derived from the names of astronomical bodies or mythological characters.

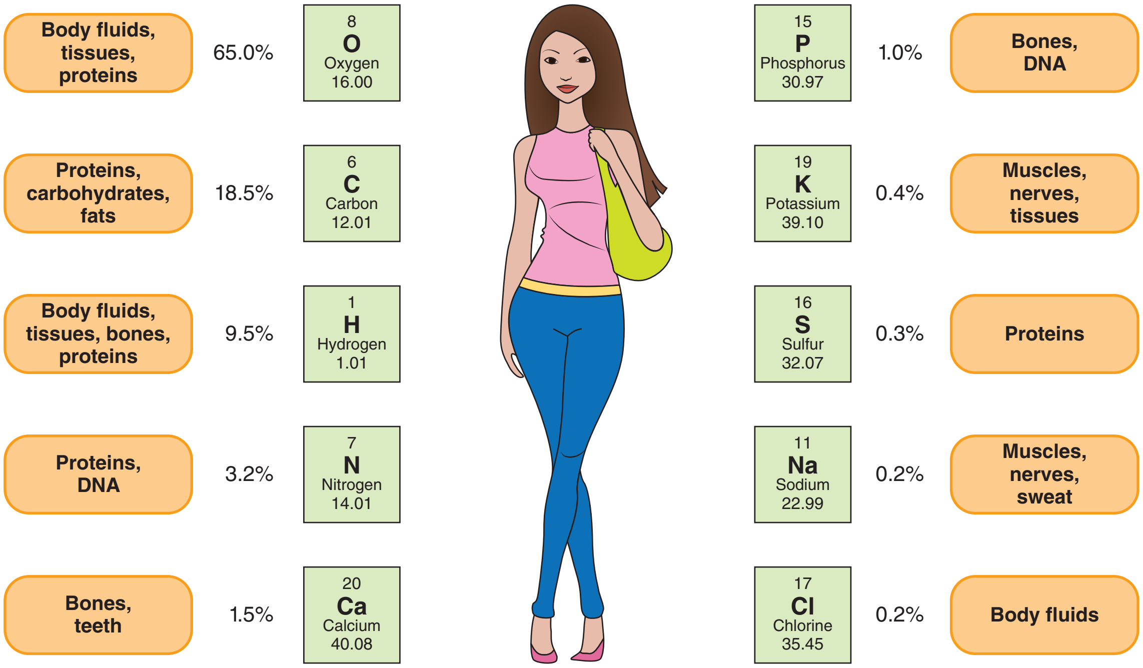

Body fluids, tissues, proteins
65.0%
8 O Oxygen 16.00
Proteins, carbohydrates, fats
18.5%
6 C Carbon 12.01
Body fluids, tissues, bones, proteins
9.5%
1 H Hydrogen 1.01
Proteins, DNA
3.2%
7 N Nitrogen 14.01
Bones, teeth
1.5%
20 Ca Calcium 40.08
15 P Phosphorus 30.97
1.0%
Bones, DNA
19 K Potassium 39.10
0.4%
Muscles, nerves, tissues
16 S Sulfur 32.07
0.3%
Proteins
11 Na Sodium 22.99
0.2%
Muscles, nerves, sweat
17 Cl Chlorine 35.45
0.2%
Body fluids

FIGURE 2.1 The human body, like all matter, is made up of chemical elements.

elemental symbol A symbol assigned to an element based on the name of the element, consisting of one capital letter or a capital letter followed by a lowercase letter.

An **elemental symbol** is based on the element's name and consists of a single capital letter or a capital letter followed by a lowercase letter. The symbols for 11 elements are based on the element's name in Latin or German. An elemental symbol is sometimes used to represent an element in a general way or to represent a single atom of an element. **Table 2.1** lists the elements whose names and symbols have been agreed on.

Compounds are pure substances made up of two or more different kinds of atoms. The atoms found in compounds are the same ones found in elements. Thus, the symbols used to represent elements can be combined and used to represent compounds. A molecular compound is depicted by a **compound formula**, in which each atom is represented by an appropriate elemental symbol. When more than one atom of an element is present in a molecule, a subscript is used to indicate the number.

compound formula A representation of the molecule of a compound, consisting of the symbols of the atoms found in the molecule. Atoms present in numbers greater than one have the number indicated by a subscript.

Notice the similarity between this practice and the molecular representations in **Figure 1.6**. The carbon dioxide molecules in **Figure 1.6** are represented by the formula CO_2, where C represents an atom of carbon and O an atom of oxygen. The subscript 2 on the oxygen indicates that the molecule contains two atoms of oxygen. Notice that the

TABLE 2.1 The Chemical Elements and Their Symbols

Ac	actinium	Es	einsteinium	Mt	meitnerium	Sb	antimony (*stibium*)[a]
Ag	silver (*argentum*)[a]	Eu	europium	N	nitrogen	Sc	scandium
Al	aluminum	F	fluorine	Na	sodium (*natrium*)[a]	Se	selenium
Am	americium	Fe	iron (*ferrum*)[a]	Nb	niobium	Sg	seaborgium
Ar	argon	Fl	flerovium	Nd	neodymium	Si	silicon
As	arsenic	Fm	fermium	Ne	neon	Sm	samarium
At	astatine	Fr	francium	Nh	nihonium	Sn	tin (*stannum*)[a]
Au	gold (*aurum*)[a]	Ga	gallium	Ni	nickel	Sr	strontium
B	boron	Gd	gadolinium	No	nobelium	Ta	tantalum
Ba	barium	Ge	germanium	Np	neptunium	Tb	terbium
Be	beryllium	H	hydrogen	O	oxygen	Tc	technetium
Bh	bohrium	He	helium	Og	oganesson	Te	tellurium
Bi	bismuth	Hf	hafnium	Os	osmium	Th	thorium
Bk	berkelium	Hg	mercury (*hydrargyrum*)[a]	P	phosphorus	Ti	titanium
Br	bromine	Ho	holmium	Pa	protactinium	Tl	thallium
C	carbon	Hs	hassium	Pb	lead (*plumbum*)[a]	Tm	thulium
Ca	calcium	I	iodine	Pd	palladium	Ts	tennessine
Cd	cadmium	In	indium	Pm	promethium	U	uranium
Ce	cerium	Ir	iridium	Po	polonium	V	vanadium
Cf	californium	K	potassium (*kalium*)[a]	Pr	praseodymium	W	tungsten (*wolfram*)[a]
Cl	chlorine	Kr	krypton	Pt	platinum	Xe	xenon
Cm	curium	La	lanthanum	Pu	plutonium	Y	yttrium
Cn	copernicium	Li	lithium	Ra	radium	Yb	ytterbium
Co	cobalt	Lr	lawrencium	Rb	rubidium	Zn	zinc
Cr	chromium	Lu	lutetium	Re	rhenium	Zr	zirconium
Cs	cesium	Lv	livermorium	Rf	rutherfordium		
Cu	copper (*cuprum*)[a]	Mc	moscovium	Rg	roentgenium		
Db	dubnium	Md	mendelevium	Rh	rhodium		
Ds	darmstadtium	Mg	magnesium	Rn	radon		
Dy	dysprosium	Mn	manganese	Ru	ruthenium		
Er	erbium	Mo	molybdenum	S	sulfur		

[a] Elements with symbols not derived from their English names.

single carbon atom in the molecule is not indicated by a subscript 1. Subscript 1 is never used in molecular formulas; it is understood. Formulas for molecular compounds are sometimes used to represent a compound in a general way, or to represent a single molecule of a compound. See **Table 2.2** and **Figure 2.2** for other examples of compound formulas.

TABLE 2.2 Examples of Compound Formulas

Compound Name	Molecular Representation	Molecular Formula
Methane		CH_4
Water		H_2O
Carbon monoxide		CO
Hydrogen peroxide		H_2O_2

Cengage Learning Steven Hyatt

FIGURE 2.2 Iron pyrite is a mineral that contains iron and sulfur atoms in a 1:2 ratio, respectively. The golden crystals, called "fool's gold" by experienced miners, have caused (temporary) excitement for many novice prospectors. What is the formula for iron pyrite?

Example 2.1 Writing Compound Formulas

Write formulas for the following compounds:

a. Nitrogen dioxide: one nitrogen (N) atom and two oxygen (O) atoms
b. Sulfuric acid: two hydrogen (H) atoms, one sulfur (S) atom, and four oxygen (O) atoms

Solution

a. The single N atom will not have a subscript because ones are understood and never written. The two O atoms will be represented by writing a subscript 2. The molecular formula is NO_2.
b. Using similar reasoning, the H atom will have a subscript 2, the S atom will have no subscript, and the O atom will have a subscript 4. Therefore, the molecular formula is H_2SO_4.

✔ **LEARNING CHECK 2.1** Write molecular formulas for the following compounds:

a. Phosphoric acid: three hydrogen (H) atoms, one phosphorus (P) atom, and four oxygen (O) atoms
b. Sulfur trioxide: one sulfur (S) atom and three oxygen (O) atoms
c. Glucose: six carbon (C) atoms, twelve hydrogen (H) atoms, and six oxygen (O) atoms

2.2 Inside the Atom

Learning Objective 2 Identify the characteristics of protons, neutrons, and electrons.

An atom has been defined as the limit of chemical subdivision for matter. On the basis of the characteristics of atoms that have been discussed, you probably would have a general (and correct) idea that atoms can be considered to be the units from which matter is made. However, the question of how atoms interact to form matter has not yet been addressed. This interesting topic will be discussed in Chapters 3 and 4, but a bit more must be learned about atoms first.

Extensive experimental evidence collected since the middle of the 19th century indicates that atoms are made up of many smaller particles. More than 100 of these subatomic particles have been discovered, and the search for more continues. As yet there is no single theory that can explain all observations involving subatomic particles, but three fundamental particles are included in all current theories: the proton, the neutron, and the electron. Most chemical behavior of matter can be explained in terms of a few of the well-known characteristics of these particles. These important characteristics are mass, electrical charge, and location in atoms. They are summarized in **Table 2.3**. The atomic mass unit (u) shown in the table is discussed in **Section 2.4**.

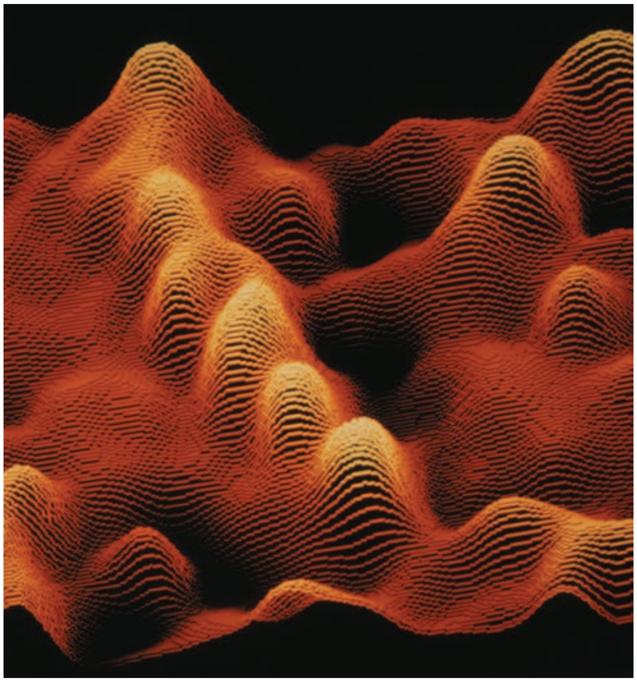
TABLE 2.3 Characteristics of the Fundamental Subatomic Particles

		Characteristics			
Particle	**Common Symbols**	**Charge (±)**	**Mass (g)**	**Mass (u)**	**Location**
Electron	e^-	1−	9.07×10^{-28}	1/1836	Outside nucleus
Proton	p, p^+, H^+	1+	1.67×10^{-24}	1	Inside nucleus
Neutron	n	0	1.67×10^{-24}	1	Inside nucleus

In Chapter 1, atoms were described as being very tiny particles (see **Figure 2.3**). The masses of single atoms of the elements are now known to fall within the range of 1.67×10^{-24} g for the least massive to 5.00×10^{-22} g for the most massive. Thus, it is not surprising to find that the particles that make up atoms have very small masses as well. Even though atomic masses are very small, the mass information given in **Table 2.3** indicates that most of the mass of an atom comes from the protons and neutrons it contains. The protons and neutrons are tightly bound together to form the central portion of an atom called the **nucleus**. Since each proton have +1 electrical charge, and neutrons have no charge, therefore nucleus of an atom has a positive electrical charge that is equal to the number of protons it contains.

nucleus The central core of atoms that contains protons, neutrons, and most of the mass of atoms.

Electrons are negatively charged particles located outside the nucleus of an atom. Protons and electrons carry equal but opposite electrical charges, so a neutral atom that has no electrical charge must have the same number of protons in its nucleus as it



Lawrence Livermore National Laboratory/Science Source

FIGURE 2.3 A view from a scanning tunneling microscope (STM) shows the locations of atoms protruding from a short strand of a DNA double helix.

has electrons outside the nucleus. The electrons of an atom are thought to move very rapidly throughout a relatively large volume of space surrounding the small but very heavy nucleus (see **Figure 2.4**).

Even though subatomic particles exist, the atom itself is the particle of primary interest in chemistry, because subatomic particles do not lead an independent existence for any appreciable length of time. The only way they gain long-term stability is by combining with other particles to form an atom.

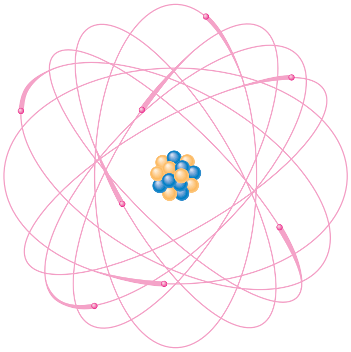


FIGURE 2.4 Electrons move rapidly around a massive nucleus. This figure is not drawn to scale. For a nucleus of the size shown, the closest electrons would be at least 80 m away.

2.3 Isotopes

Learning Objective 3 Use the concepts of atomic number and mass number to determine the number of subatomic particles in isotopes and to write correct symbols for isotopes.

Since atoms of elements have no electrical charge, so must contain identical numbers of positive protons and negative electrons. However, because neutrons have no electrical charge, their number in an atom do not have to be the same as the numbers of protons or electrons. The number of protons in the nucleus of an atom is given by the **atomic number** for the atom. Atomic numbers are represented by the symbol *Z*. All atoms of a specific element must have the same atomic number. The atomic numbers for each element are the numbers above the elemental symbols of the periodic table inside the front cover of this book. Remember, this is also the number of electrons in the atoms of each element.

atomic number of an atom A number equal to the number of protons in the nucleus of an atom. Symbolically it is represented by *Z*.

The possibility of having different numbers of neutrons combined with one given number of protons to form nuclei leads to some interesting results. For example, three different kinds of hydrogen atoms are known to exist. Each kind of atom contains one proton and one electron, so all have an atomic number of 1. However, the nuclei of the different kinds of hydrogen atoms contain different numbers of neutrons. The most common kind has no neutrons in the nucleus, the next most common has one, and the least common kind has two. The sum of the number of protons and the number of neutrons in a nucleus is called the **mass number** and is represented by the symbol *A*. Thus, all the three different kinds of hydrogen atoms have atomic numbers of 1 and mass numbers of 1, 2, and 3, respectively. Atoms that have the same atomic number but different mass numbers are called **isotopes**. Most elements are made up of mixtures of two or more isotopes. **Figure 2.5** shows the element silicon, one of the major elements in the Earth's crust; it has 23 known isotopes. It is important to distinguish between them, so the following notation is used for each isotope: ${}^{A}_{Z}E$, where *E* is the symbol for the element.

The three isotopes of hydrogen are represented as follows using this notation: ${}^{1}_{1}\mathrm{H}$, ${}^{2}_{1}\mathrm{H}$, and ${}^{3}_{1}\mathrm{H}$. When these symbols are not convenient to use, as in written or spoken references to the isotopes, the elemental name followed by the mass number is used. Thus, the three hydrogen isotopes are hydrogen-1, hydrogen-2, and hydrogen-3. These three isotopes have specific names as: protium ($A = 1$), deuterium ($A = 2$), and tritium ($A = 3$) respectively.

mass number of an atom A number equal to the sum of the number of protons and neutrons in the nucleus of an atom. Symbolically it is represented by *A*.

isotopes Atoms that have the same atomic number but different mass numbers. That is, they are atoms of the same element that contain different numbers of neutrons in their nuclei.

Example 2.2 Using the Periodic Table

Use the periodic table present on the front cover to answer the following questions about isotopes:

a. What are the mass number, atomic number, and isotope symbol (${}^{A}_{Z}E$) for an atom that contains 7 protons and 8 neutrons?

b. How many neutrons are contained in an atom of nickel-60? Nickel is used in the production of stainless steel, including many pieces of medical equipment.

c. How many protons and neutrons are contained in an atom with a mass number of 26 and the symbol Mg?

Bokeh Art Photo/Shutterstock.com

FIGURE 2.5 Silicon has 23 known isotopes.

Solution

a. The mass number, *A*, is equal to the sum of the number of protons and the number of neutrons: $A = 7 + 8 = 15$. The atomic number, *Z*, is equal to the number of protons: $Z = 7$. According to the periodic table, the element with an atomic number 7 is nitrogen, with the symbol N. Hence, isotope symbol will be ${}^{15}_{7}\mathrm{N}$.

b. According to the periodic table, nickel has the symbol Ni, and an atomic number, Z, of 28. The mass number, 60, which is equal to the sum of the number of protons and the number of neutrons. The number of protons is equal to the atomic number, 28. Therefore, the number of neutrons is $60 - 28 = 32$. The atom contains 32 neutrons.

c. According to the periodic table, the element with the symbol Mg is magnesium, which has an atomic number of 12. Therefore, the atom contains 12 protons. Since A, the number of protons plus neutrons is equal to 26, Therefore, number of neutrons is $26 - 12$, or 14. The atom contains 14 neutrons.

✔ **LEARNING CHECK 2.2** Use the periodic table present on the front cover to answer the following questions about isotopes:

a. What are the atomic number, mass number, and isotope symbol for an atom that contains 4 protons and 5 neutrons?

b. How many neutrons are contained in an atom of chlorine-37?

c. How many protons and neutrons are contained in an atom with a mass number of 28 and the symbol Si?

2.4 Relative Masses of Atoms and Molecules

Learning Objective 4 Use atomic weights of the elements to calculate molecular weights of compounds.

Because of their extremely small size, it is very inconvenient to use the actual masses of atoms when the atoms are being characterized or when quantitative calculations are done. In fact, the earliest chemists had no way of determining the actual masses of atoms. For this reason, a system was devised that utilized relative or comparative masses for the atoms. These relative masses are the numbers that are given beneath the symbol and name for each element in the periodic table inside the front cover.

Relative masses provide a simple way of comparing the masses of atoms. For example, the mass of neon atoms, Ne, from the periodic table is given as 20.18 (see **Figure 2.6**). Similarly, the mass of calcium atoms, Ca, is given as 40.08. These numbers simply indicate that calcium atoms have a mass that is about twice the mass of neon atoms. The exact relationship between the two masses is calculated as follows, using the correct number of significant figures:

PublicDomainPictures/17907/Pixabay

FIGURE 2.6 Neon is an inert gas well-known for its use in signage.

$$\frac{\text{Ca atomic mass}}{\text{Ne atomic mass}} = \frac{40.08}{20.18} = 1.986$$

In a similar way, we arrive at the conclusion that helium atoms are about four times as massive as hydrogen atoms:

$$\frac{\text{He atomic mass}}{\text{H atomic mass}} = \frac{4.003}{1.008} = 3.971$$

In each case, we have been able to determine the relationship between the masses of different atoms without using their actual masses.

Modern instruments called mass spectrometers allow the actual masses of individual atoms to be measured. These measured of different elements show the same relationships to each other as do the relative masses:

$$\frac{\text{Ca atomic mass}}{\text{Ne atomic mass}} = \frac{6.655 \times 10^{-23}\ \text{g}}{3.351 \times 10^{-23}\ \text{g}} = 1.986$$

$$\frac{\text{He atomic mass}}{\text{H atomic mass}} = \frac{6.647 \times 10^{-24}\ \text{g}}{1.674 \times 10^{-24}\ \text{g}} = 3.971$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS **2.1**

Uprooting Herbal Myths

Truth is seldom final or absolute; it depends on the kind and amount of evidence that substantiates it. Too often, the selection of herbs used as medications is based on common myths. See if any of these sound familiar. Are they fact or fallacy?

MYTH: Herbs are natural, so they are “safe and effective.”

TRUTH: Many herbs are “safe,” but never consider all natural substances as safe. There are many natural compounds that are very dangerous—think of hemlock, cyanide, and botulinum. Herbs are not required by law to be proven safe and effective before they are marketed. The “effectiveness” of a compound could be influenced by how it was grown, harvested, and prepared for use.

MYTH: You don’t need to tell your doctor that you’re taking herbs.

TRUTH: Don’t romanticize a “natural benefit” and ignore potential risks. If an herb has enough potency to cause a desired effect, it might have enough potency to cause harm or confound a treatment plan. Taking ginkgo for cognitive improvement might interfere with blood coagulation. Ma huang taken to suppress appetite might aggravate mood/anxiety disorders. There are many well-described drug–herb interactions that need to be avoided.

MYTH: If it is on the label, it must be true.

TRUTH: Herbal therapies are not governed by the FDA and, consequently do not have to conform to the labeling requirements for prescription (Rx) or over-the-counter (OTC) medications. Herbal supplements fall under the Dietary Supplement Health and Education Act (DSHEA) of 1994, which allows structure and function claims on the label.

MYTH: I don’t need special training to take herbs.

TRUTH: Since there is less reliable information available about herbs, and there are few safeguards in a relatively unregulated industry, it is even more important to have special training to allow for an objective, informed decision to be made.

Reliable information can be obtained from the National Center for Complementary and Alternative Medicine funded by the National Institutes of Health.

ArCaLu/Shutterstock.com

Be sure to tell your doctor if you are taking herbal products.

Thus, we see that the relative masses used in the periodic table give the same results as the actual masses, when the masses of different atoms are compared with one another.

Actual atomic masses are given in mass units such as grams, but the relative values used in the periodic table are given in units referred to as **atomic mass units**. The symbol “u” will be used to represent atomic mass units throughout the text. The actual mass represented by a single atomic mass unit is $\frac{1}{12}$ of the mass of a single carbon-12 atom or 1.661×10^{-24} g.

atomic mass unit (u) A unit used to express the relative masses of atoms. One u is equal to $\frac{1}{12}$ the mass of an atom of carbon-12.

The relative masses of the elements as given in the periodic table are referred to as atomic masses or atomic weights. We will use the term **atomic weight** in this book. In those cases where the naturally occurring element exists in the form of a mixture of isotopes, the recorded atomic weight is the average value for the naturally occurring isotope mixture. This idea is discussed in **Section 2.5**.

atomic weight The mass of an average atom of an element expressed in atomic mass units.

A convenient way to visualize the concept of relative masses, and to compare the relative masses of atoms, involves the use of the simple child’s toy called a seesaw or teeter-totter, shown below.

When the masses on both sides of the central pivot are equal, the seesaw will be in balance. When the masses on each side are different, the seesaw will be out of balance, and the side

HEALTH CONNECTIONS **2.2**

Take Care of Your Bones

Osteoporosis, the abnormal thinning of bones that often accompanies aging, may lead to bone fractures, disability, and even death. While women are most susceptible, this serious condition also affects men, but usually at a more advanced age than women. A number of significant risk factors have been identified, including the following:

1. A poor diet, especially one low in calcium
2. Advanced age
3. The onset of menopause (or having had ovaries removed)
4. A sedentary lifestyle
5. Smoking
6. A family history of osteoporosis or hip fracture
7. Heavy drinking
8. The long-term use of certain steroid drugs
9. Vitamin D deficiency

Ninety-nine percent of the calcium found in the body is located in the skeleton and teeth, so it is not surprising that the behavior of this metallic element in the body plays a central role in a number of these risk factors for osteoporosis.

It is well recognized that the best insurance against developing osteoporosis in later life is to build and strengthen as much bone as possible during the first 25 to 35 years of life. Two essential components of this process are eating a healthful diet containing adequate amounts of calcium and vitamin D, and following a healthful lifestyle that includes regular weight-bearing exercise such as walking, jogging, weight lifting, stair climbing, or physical labor. Dietary calcium supplements provide an additional way to enhance calcium intake, especially for individuals who are at risk to develop osteoporosis.

Sally Ho/Getty Images

An active lifestyle is an essential component of building and strengthening bones.

with the greatest mass will go down. This characteristic lends itself to compare the masses of different objects to each other without knowing their actual values in mass units such as grams.

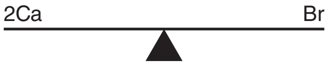
Example 2.3 Atomic Weight Calculations

Round the atomic weights of the periodic table to the nearest whole number, and answer the following questions:

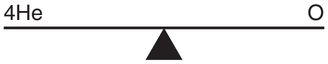
a. How many calcium atoms, Ca, would have to be put on one side of a seesaw to balance one atom of bromine, Br, that was placed on the other side?
b. How many helium atoms, He, would balance one oxygen atom on a seesaw?
c. How many hydrogen atoms, H, would balance one carbon atom, C, on a seesaw?

Solution

a. Calcium atoms have a periodic table atomic weight of 40.08 u, which rounds to 40 u. Bromine atoms have a periodic table atomic weight of 79.90 u, which rounds to 80 u. Thus, two calcium atoms would be required to balance one bromine atom as indicated below:

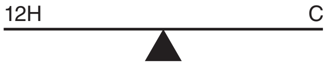


b. Helium atoms have a periodic table atomic weight of 4.003 u, which rounds to 4 u. Oxygen atoms have a periodic table atomic weight of 16.00 u, which rounds to 16 u. Thus, four helium atoms will balance one oxygen atom as shown below:



Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

c. Hydrogen atoms have a periodic table atomic weight of 1.008 u, which rounds to 1 u. Carbon atoms have a periodic table atomic weight of 12.01 u, which rounds to 12 u. Hence, twelve hydrogen atoms will balance one carbon atom as shown below:



✔ **LEARNING CHECK 2.3** Round atomic weights of the periodic table to the nearest whole number, and answer the following questions using the seesaw balance idea:

a. How many nitrogen atoms, N, will balance one atom of iron, Fe?
b. How many carbon atoms, C, will balance six helium atoms, He?
c. How many calcium atoms, Ca, will balance two argon atoms, Ar?

Molecules are made up of atoms, so the relative mass of a molecule can be calculated by adding together the atomic weights of the various atoms that make up the molecule. Relative molecular masses calculated in this way are called **molecular weights** and are also given in atomic mass units.

molecular weight The relative mass of a molecule expressed in atomic mass units and can be calculated by adding together the atomic weights of the atoms in the molecule.

Example 2.4 Atomic Weights and Molecular Weights

Use atomic weights from the periodic table inside the front cover to determine the molecular weight of urea, CH_4N_2O, the chemical form through which much nitrogenous body waste is excreted out in the urine (see **Figure 2.7**).

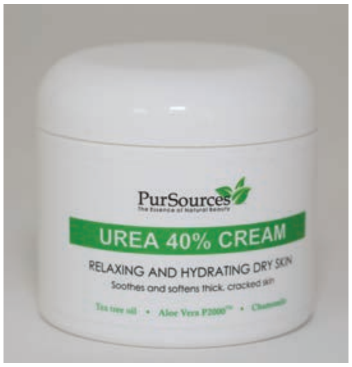
Solution

According to the formula given, a urea molecule contains one carbon atom, C, four hydrogen atoms, H, two nitrogen atoms, N, and one oxygen atom, O. The molecular weight is calculated as follows:

$$\text{MW} = 1(\text{at. wt. C}) + 4(\text{at. wt. H}) + 2(\text{at. wt. N}) + 1(\text{at. wt. O})$$

$$\text{MW} = 1(12.01\ \text{u}) + 4(1.008\ \text{u}) + 2(14.01\ \text{u}) + 1(16.00\ \text{u}) = 60.062\ \text{u}$$

Rounded to four significant figures, the correct answer is 60.06 u.


PurSources
UREA 40% CREAM
RELAXING AND HYDRATING DRY SKIN
Soothes and softens thick, cracked skin

Helen/Alamy Stock Photo

FIGURE 2.7 Urea is used to treat dry/rough skin conditions.

✔ **LEARNING CHECK 2.4**

a. Use atomic weights from the periodic table to determine the molecular weight of sulfuric acid. Each molecule contains two hydrogen (H) atoms, one sulfur (S) atom, and four oxygen (O) atoms.
b. Determine the molecular weight of isopropyl alcohol (C_3H_8O), the active ingredient in most rubbing alcohol sold commercially.

2.5 Isotopes and Atomic Weights

Learning Objective 5 Use isotope percent abundances and masses to calculate atomic weights of elements.

The atomic weights discussed in **Section 2.4** were defined as the relative masses of atoms of the elements. It would have been more correct to define them as the relative masses of average atoms of the elements. Why to include the idea of an average atom? Remember, the mass number of an isotope is the sum of the number of protons and neutrons in the nucleus of atoms of the isotope. Also, protons and neutrons both have masses of 1 u (see **Table 2.3**). The masses of electrons are quite small, so the atomic weights of isotopes are very nearly equal to their mass numbers. For example, all naturally occurring phosphorus is made up of atoms containing 15 protons and 16 neutrons. The mass number of this isotope is 31, and its symbol is $^{31}_{15}P$. The relative mass (atomic weight) of atoms of this isotope is 30.97 u, the same as the atomic weight of the element given in the periodic table. The atomic weight of the isotope and the listed atomic weight of the element are the same, because all atoms contained in the element are identical and have the same relative mass.

Naturally occurring chlorine is different. It is a mixture of two isotopes, $^{35}_{17}Cl$ and $^{37}_{17}Cl$. Chlorine-35 has a mass number of 35 and a relative mass of 34.97 u. Chlorine-37 has a mass number of 37 and a relative mass of 36.97 u. Note that the mass numbers and relative masses (atomic weights) of the atoms of an isotope are essentially identical. However, naturally occurring chlorine is a mixture of both isotopes. Thus, the determined relative mass of chlorine atoms will be the average relative mass of the atoms found in the mixture (see **Figure 2.8**).

MSPhotographic/Shutterstock.com

FIGURE 2.8 The pieces of fruit in a bowl are somewhat like atoms of the isotopes of an element. Each piece of fruit may have the same color, taste, and texture, but it is unlikely that any two have *exactly* the same mass. The 12 oranges in the bowl weigh a total of 2.36×10^3 g. What is the average mass of each orange in the bowl?

The average mass of each particle in a group of particles is simply the total mass of the group divided by the number of particles in the group. This calculation requires that the total number of particles be known. However, the percentage of each isotope in a mixture of atoms is easier to determine than the actual number of atoms of each isotope present. The percentages can be used to calculate average masses. Remember that percent means per 100, so we use an imaginary sample of an element containing 100 atoms in the calculation. On this basis, the number of atoms of each isotope in the 100-atom sample will be the percentage of that isotope in the sample. The mass contributed to the sample by each isotope will be the product of the number of atoms of the isotope (the percentage of the isotope) and the mass of the isotope. The total mass of the sample will be the sum of the masses contributed by each isotope. This total mass divided by 100, (the number of atoms in our imaginary sample), gives the mass of an average atom, which is the atomic weight of the element.

Example 2.5 Isotope and Atomic Weight Relationships

Chlorine is a disinfectant and is used to treat drinking water and swimming pool water.

Calculate the atomic weight of chlorine, given that the naturally occurring element consists of 75.53% chlorine-35 (mass = 34.97 u) and 24.47% chlorine-37 (mass = 36.97 u).

Solution

$$\text{Atomic weight} = \frac{(\%\text{ chlorine-35})(\text{mass chlorine-35}) + (\%\text{ chlorine-37})(\text{mass chlorine-37})}{100}$$

$$= \frac{(75.53)(34.97\text{ u}) + (24.47)(36.97\text{ u})}{100}$$

$$= \frac{2641.28\text{ u} + 904.66\text{ u}}{100} = \frac{3545.94\text{ u}}{100} = 35.4594\text{ u}$$

$$= 35.46\text{ u (rounded value)}$$

This result is slightly different from the periodic table atomic weight value of 35.45 because of slight errors introduced in rounding the isotope masses to four significant figures.

✔ LEARNING CHECK 2.5

a. Naturally occurring fluorine consists of a single isotope, fluorine-19, with a mass of 19.00 u (using four significant figures). Determine the atomic weight of fluorine, and compare your answer with the value given in the periodic table.
b. Naturally occurring magnesium has three isotopes: magnesium-24, magnesium-25, and magnesium-26. Their relative masses and percent abundances are, respectively, 23.99 u (78.70%), 24.99 u (10.13%), and 25.98 u (11.17%). Determine the atomic weight of magnesium, and compare it with the value given in the periodic table.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

24.31 g of **magnesium**

© Jeffrey M. Seager

12.01 g of **carbon**

© Jeffrey M. Seager

FIGURE 2.9 Samples of magnesium and carbon with masses of 24.31 g and 12.01 g, respectively.

2.6 Avogadro's Number: The Mole

Learning Objective 6 Use the mole concept to obtain relationships between number of moles, number of grams, and number of atoms for elements, and use those relationships to obtain factors for use in factor-unit calculations.

The atomic weights of the elements given in the periodic table have far more uses than simply comparing the masses of the atoms of various elements. However, these uses are not apparent until some additional ideas are developed. According to the periodic table, the atomic weight of magnesium, Mg, is 24.31 u, and the atomic weight of carbon, C, is 12.01 u. This means that an average magnesium atom has about twice the mass of an average carbon atom. Modern instruments allow us to determine that the actual mass of an average magnesium atom is 4.037×10^{-23} g, and the actual mass of an average carbon atom is 1.994×10^{-23} g.

Even though the actual masses of magnesium and carbon atoms are extremely small, it should still be possible to collect together enough atoms of either element to give a sample of any desired mass. Suppose we wish to collect together enough atoms of each element to give a sample with a mass in grams equal to the atomic weight of each element. That is, we want to collect enough magnesium atoms to give a sample with a total mass of 24.31 g, and enough carbon atoms to give a sample with a total mass of 12.01 g (see **Figure 2.9**). How many atoms of each element will be required?

We know the mass of one atom of each element, and this fact will provide us with a factor that will allow us to convert the desired sample mass into the number of atoms required. The given mass of one atom of magnesium can be written as

$$1 \text{ Mg atom} = 4.037 \times 10^{-23} \text{ g Mg}$$

This known relationship provides two factors that can be used to solve factor-unit problems:

$$\frac{1 \text{ Mg atom}}{4.037 \times 10^{-23} \text{ g Mg}} \quad \text{and} \quad \frac{4.037 \times 10^{-23} \text{ g Mg}}{1 \text{ Mg atom}}$$

Our task is to convert the desired sample mass of 24.31 g Mg into the number of Mg atoms in the sample. The first factor will cancel the units "g Mg" and will generate the units "Mg atoms."

$$(24.31 \cancel{\text{g Mg}}) \times \frac{1 \text{ Mg atom}}{4.037 \times 10^{-23} \cancel{\text{g Mg}}} = 6.022 \times 10^{23} \text{ Mg atoms}$$

In a similar way, the number of C atoms needed to produce a sample with a mass of 12.01 g is calculated:

$$(12.01 \cancel{\text{g C}}) \times \frac{1 \text{ C atom}}{1.994 \times 10^{-23} \cancel{\text{g C}}} = 6.023 \times 10^{23} \text{ C atoms}$$

The result that the same number of atoms is required for each sample might seem surprising, but it is a consequence of the sample sizes we wanted to produce. If we collected just one atom of each element, the ratio of the mass of Mg to the mass of C would be equal to the atomic weight of Mg divided by the atomic weight of C:

$$\frac{\text{Mg mass}}{\text{C mass}} = \frac{4.037 \times 10^{-23} \cancel{\text{g}}}{1.994 \times 10^{-23} \cancel{\text{g}}} = 2.024 = \frac{\text{At. wt. Mg}}{\text{At. wt. C}} = \frac{24.31 \cancel{\text{u}}}{12.01 \cancel{\text{u}}}$$

This result reflects the fact that magnesium atoms have about twice the mass of carbon atoms. If we collect samples of 100 atoms of each element, the ratio of the mass of the Mg sample to the mass of the C sample would still be 2.024, because each sample would have a mass 100 times greater than the mass of a single atom:

$$\frac{\text{Mg mass}}{\text{C mass}} = \frac{(100)(4.037 \times 10^{-23} \cancel{\text{g}})}{(100)(1.994 \times 10^{-23} \cancel{\text{g}})} = 2.024$$

It follows that if we collect samples containing 6.022 × 10^{23} atoms of each element, the ratio of the mass of the Mg sample to the mass of the C sample would still be 2.024 because each sample would have a mass that would be 6.022 × 10^{23} times greater than the mass of a single atom:

$$\frac{\text{Mg mass}}{\text{C mass}} = \frac{(6.023 \times 10^{23})(4.037 \times 10^{-23}\ \cancel{g})}{(6.023 \times 10^{23})(1.994 \times 10^{-23}\ \cancel{g})} = 2.024$$

These results lead to the following conclusion: Any samples of magnesium and carbon that have mass ratios equal to 2.024 will contain the same number of atoms.

Example 2.6 Mass Ratios and Atomic Weights

Magnesium compounds have a number of medical uses, including the treatment of acid indigestion and heartburn. Carbon compounds are found in all living cells (see **Figure 2.10**).

Show that samples of magnesium and carbon with masses of 9.663 g and 4.774 g, respectively, have a mass ratio of 2.024 and contain the same number of atoms.

Brocreative/Shutterstock.com

FIGURE 2.10 Carbon is the building block of all cells in the body.

Solution

The mass ratio is obtained by dividing the mass of the magnesium sample by the mass of the carbon sample:

$$\frac{\text{Mg mass}}{\text{C mass}} = \frac{9.663\ \text{g}}{4.774\ \text{g}} = 2.024$$

The number of atoms in each is calculated using the factors obtained earlier from the mass of one atom of each element:

$$(9.663\ \cancel{\text{g Mg}}) \times \frac{1\ \text{Mg atom}}{4.037 \times 10^{-23}\ \cancel{\text{g Mg}}} = 2.394 \times 10^{23}\ \text{Mg atoms}$$

$$(4.774\ \cancel{\text{g C}}) \times \frac{1\ \text{C atom}}{1.994 \times 10^{-23}\ \cancel{\text{g C}}} = 2.394 \times 10^{23}\ \text{C atoms}$$

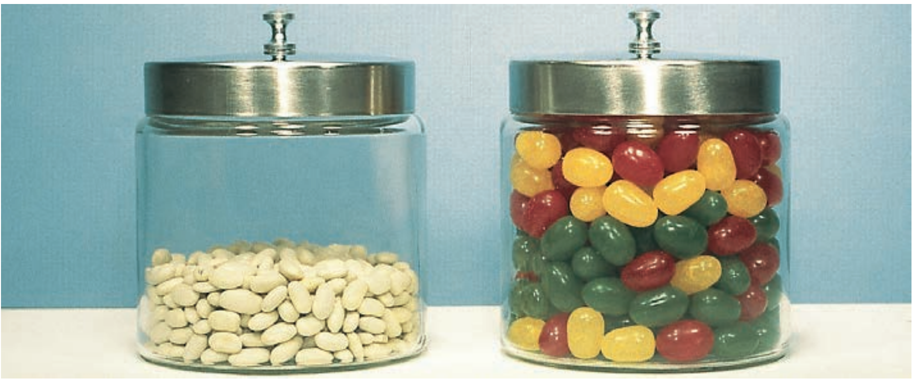
✔ **LEARNING CHECK 2.6** Show that samples of magnesium and carbon with masses 13.66 g and 6.748 g, respectively, have a mass ratio of 2.024 and contain the same number of atoms.

The preceding results for magnesium and carbon may be generalized for all the elements of the periodic table as follows. Any samples of two elements that have a mass ratio equal to the ratio of their atomic weights will contain identical numbers of atoms. In addition, we have seen that if the number of grams of sample is equal numerically to the atomic weight of an element, then the number of atoms in that sample will be equal to 6.022 × 10^{23}. **Figure 2.11** illustrates these ideas for particles that are familiar to most of us.

With modern equipment, it is possible to determine the number of atoms of any size sample in an element. However, before this was possible, the practice of focusing on samples with a mass in grams equal to the atomic weights of the elements became well established and it continues till today. We have learned that the number of atoms in such samples is 6.022 × 10^{23}.

We saw in **Section 2.4** that molecular weights, the relative masses of molecules, are calculated by adding the atomic weights of the atoms contained in the molecules. The resulting molecular weights are expressed in atomic mass units, just as are the atomic weights of the atoms. The same ideas we used to discuss the actual and relative masses of atoms can be applied to molecules. We will not go through the details, but simply state the

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.



© Spencer L. Seager

FIGURE 2.11 An average jelly bean has a mass that is 1.60 times the mass of an average dry bean. Each jar contains the same number of beans. The total mass of jelly beans is 472 g. What is the total mass of the dry beans?

primary conclusion: A sample of a compound with a mass in grams equal to the molecular weight of the compound contains 6.022×10^{23} molecules of that compound.

The number 6.022×10^{23} is called *Avogadro's number* in honor of Amedeo Avogadro (1776–1856), an Italian scientist who made important contributions to the concept of atomic weights. As we have seen, this number represents the number of atoms or molecules in a specific sample of an element or compound. Because of its importance in calculations, the number of particles represented by Avogadro's number is given a specific name; it is called a **mole**, abbreviated as mol.

mole The number of particles (atoms or molecules) contained in a sample of an element or compound with a mass in grams equal to the atomic or molecular weight, respectively. Numerically, 1 mol is equal to 6.022×10^{23} particles.

It is sometimes helpful to remember that the word *mole* represents a specific number, just as the word *dozen* represents 12, regardless of the objects being counted. Thus, 6.022×10^{23} people would be called 1 mol of people, just as 12 people would be called 1 dozen people. The immensity of Avogadro's number is illustrated by the results of a few calculations based on 1 mol of people. One mol of people would be enough to populate about 1×10^{14} Earths at today's level. That is 100 trillion Earths. Or, in another way, the present population of Earth is 1×10^{-12}% (0.000000000001%) of 1 mol.

In the development of these ideas to this point, we have used four significant figures for atomic weights, molecular weights, and Avogadro's number to minimize the introduction of rounding errors. However, in calculations throughout the remainder of the book, three significant figures will generally be sufficient and will be used.

In a strict sense, 1 mol is a specific number of particles. However, in chemistry it is customary to follow the useful practice of also letting 1 mol stand for the mass of a sample of element or compound that contains Avogadro's number of particles. Thus, the application of the mole concept to sulfur (at. wt. = 32.1 u) gives the following relationships:

$$1 \text{ mol S atoms} = 6.02 \times 10^{23} \text{ S atoms} = 32.1 \text{ g S}$$

When written individually, the relationship among the three can be used to generate six factors for use in factor-unit calculations involving sulfur:

$$1 \text{ mol S atoms} = 6.02 \times 10^{23} \text{ S atoms}$$

$$6.02 \times 10^{23} \text{ S atoms} = 32.1 \text{ g S}$$

$$1 \text{ mol S atoms} = 32.1 \text{ g S}$$

Example 2.7 Factor-Unit Calculations for Sulfur

Sulfur is a vital element for all forms of life as a component of two amino acids (see **Table 19.1**).

Determine the following using the factor-unit method of calculation and factors obtained from the preceding three relationships given for sulfur (S):

a. The mass in grams of 1.35 mol of S
b. The number of S atoms in 98.6 g of S

Solution

a. We will use the four steps of the factor-unit method (see Study Tools 1.1). The known quantity is 1.35 mol of S, and the unit of the unknown quantity is grams of S.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STEP 1 1.35 mole S atoms

STEP 2 1.35 mole S atoms = ? g S

STEP 3 $(1.35\ \cancel{\text{mol S atoms}})\left(\dfrac{32.1\text{ g S}}{1\ \cancel{\text{mol S atoms}}}\right) = 43.3\text{ g S}$

The factor comes from the relationship 1 mol S atoms = 32.1 g S.

STEP 4 Check to see whether the answer makes sense.

Yes. The answer should be greater than 32.1 g S.

b. The known quantity is 96 g S, and the unit of the unknown quantity is atoms of S.

STEP 1 98.6 g S

STEP 2 98.6 g S = ? S atoms

STEP 3 $(98.6\ \cancel{\text{g S}})\left(\dfrac{6.02\times 10^{23}\text{ S atoms}}{32.1\ \cancel{\text{g S}}}\right) = 1.85\ \times 10^{24}\text{ S atoms}$

The factor comes from the relationship 6.02×10^{23} S atoms = 32.1 g S.

STEP 4 Check to see whether the answer makes sense.

Yes. The answer seems reasonable.

✔ LEARNING CHECK 2.7

a. Determine the number of moles of S atoms in 98.6 g of S.
b. Determine the mass in grams of one atom of S.

waraphorn-aphai/iStock/Getty Images

FIGURE 2.12 Dry ice is a solid (and very cold) form of carbon dioxide.

The mole concept can also be applied to particles that are molecules instead of atoms. The compound carbon dioxide consists of molecules that contain one carbon atom, C, and two oxygen atoms, O. The formula for the molecule is CO_2 (see **Figure 2.12**). The molecular weight of the molecule is calculated as shown earlier by adding together the atomic weight of one carbon atom and the atomic weight of two oxygen atoms:

$$\text{MW} = 1\text{ (at. wt. C)} + 2\text{ (at. wt. O)} = 1\text{ (12.0 u)} + 2\text{ (16.0 u)} = 44.0\text{ u}$$

Thus, the relative mass of a CO_2 molecule is 44.0 u, and application of the mole concept to CO_2 molecules gives the following relationships:

$$1\text{ mol } CO_2\text{ molecules} = 6.02 \times 10^{23}\ CO_2\text{ molecules} = 44.0\text{ g } CO_2$$

When written individually, these the relationship among the three can be used to generate six factors for use in factor-unit calculations involving CO_2.

$$1\text{ mol } CO_2\text{ molecules} = 6.02 \times 10^{23}\ CO_2\text{ molecules}$$

$$6.02 \times 10^{23}\ CO_2\text{ molecules} = 44.0\text{ g } CO_2$$

$$1\text{ mol } CO_2\text{ molecules} = 44.0\text{ g } CO_2$$

Paul Burns/DigitalVision/Getty Images

FIGURE 2.13 Along with water vapor, we exhale carbon dioxide.

Example 2.8 Factor-Unit Calculations for Carbon Dioxide

Atmospheric carbon dioxide (see **Figure 2.13**) is the primary carbon source for life on Earth.

Determine the following using the factor-unit method of calculation and factors obtained from the preceding three relationships given for carbon dioxide, CO_2:

a. The mass in grams of 1.62 mol of CO_2
b. The number of CO_2 molecules in 63.9 g of CO_2

Solution

a. We will use the four steps of the factor-unit method (see Study Tools 1.1). The known quantity is 1.62 mol of CO_2, and the unit of the unknown quantity is g.

STEP 1 1.62 mol CO_2 molecules

STEP 2 1.62 mol CO_2 molecules = ? g CO_2

STEP 3 $1.62\ \cancel{\text{mol CO}_2\text{ molecules}}\left(\dfrac{44.0\text{ g CO}_2}{1\ \cancel{\text{mol CO}_2\text{ molecules}}}\right) = 71.3\text{ g CO}_2$

The factor comes from the relationship 1 mol CO_2 molecules = 44.0 g CO_2

STEP 4 Check to see whether the answer makes sense.

Yes. The answer seems reasonable.

b. The known quantity is 63.9 g of CO_2, and the unit of the unknown is molecules.

STEP 1 63.9 g CO_2

STEP 2 63.9 g CO_2 = ? molecules

STEP 3 $63.9\text{ g CO}_2\left(\dfrac{6.02 \times 10^{23}\text{ CO}_2\text{ molecules}}{44.0\text{ g CO}_2}\right) = 8.74 \times 10^{23}\text{ CO}_2\text{ molecules}$

The factor comes from the relationship 6.02×10^{23} CO_2 molecules = 44.0 g CO_2.

STEP 4 Check to see if the answer makes sense.

Yes. The answer seems reasonable.

✔ LEARNING CHECK 2.8

a. Determine the number of moles of CO_2 molecules in 63.9 g of CO_2.
b. Determine the mass in grams of one molecule of CO_2.

2.7 The Mole and Chemical Formulas

Learning Objective 7 Use the mole concept and molecular formulas to obtain relationships between number of moles, number of grams, and number of atoms or molecules for compounds, and use those relationships to obtain factors for use in factor-unit calculations.

According to **Section 2.1** and as demonstrated in Example 2.8, the formula for a compound is made up of the symbols for each element present. Subscripts following the elemental symbols indicate the number of each type of atom represented in the molecule. Thus, chemical formulas represent the numerical relationships that exist among the atoms in a compound. Application of the mole concept to the atoms in making up the formulas provides additional useful information.

Consider water as an example. The formula H_2O represents a 2:1 ratio of hydrogen atoms to oxygen atoms in a water molecule. Since this ratio is fixed, the following statements can be written:

1. 2 H_2O molecules contain 4 H atoms and 2 O atoms.
2. 10 H_2O molecules contain 20 H atoms and 10 O atoms.
3. 100 H_2O molecules contain 200 H atoms and 100 O atoms.
4. 6.02×10^{23} H_2O molecules contain 12.04×10^{23} H atoms and 6.02×10^{23} O atoms.

Statement 4 is significant because 6.02×10^{23} particles is 1 mol. Thus, Statement 4 can be changed to Statement 5:

5. 1 mol of H_2O molecules contains 2 mol of H atoms and 1 mol of O atoms.

Figure 2.14 contains another example of this concept.

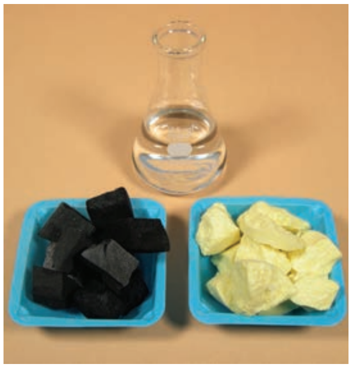

© Jeffrey M. Seager

FIGURE 2.14 Liquid carbon disulfide (CS_2) is composed of carbon (left) and sulfur (right), elements that are solids. How many moles of sulfur atoms would be contained in 1.5 mol of CS_2 molecules?

Example 2.9 Mole Calculations Using Rabbits

How many moles of ears, tails, and legs are contained in 1 mol of normal rabbits?

Solution

This example is nonchemical, but it might help you grasp the relationships that exist between the individual parts of a formula and the formula as a whole. The parts of a rabbit are related to a rabbit just as the parts of a formula are related to the entire formula.

Ears. Each rabbit has two ears and a 2:1 ratio exists between the number of ears and the number of rabbits. Therefore, 1 mol of rabbits contains 2 mol of ears.

Tails. The 1:1 ratio of tails to rabbits leads to the conclusion that 1 mol of rabbits contains 1 mol of tails.

Legs. The 4:1 ratio of legs to rabbits leads to the conclusion that 1 mol of rabbits contains 4 mol of legs.

Example 2.10 Mole Calculations Using Molecular Formulas

How many moles of each type of atom are contained in 1 mol of chloroform ($CHCl_3$)?

Solution

Just as each rabbit has two ears, each chloroform molecule contains one C atom, one H atom, and three Cl atoms. Therefore, 1 mol of $CHCl_3$ contains 1 mol of C atoms, 1 mol of H atoms, and 3 mol of Cl atoms.

✔ **LEARNING CHECK 2.9** How many moles of each type of atom would be contained in 0.50 mol of glucose ($C_6H_{12}O_6$)?

The usefulness of this approach can be increased by remembering and using the mass relationships of the mole concept. Thus, Statement 5, written earlier for water, can be changed to Statement 6:

6. 18.0 g of water contains 2.0 g of H and 16.0 g of O.

Or, in a more concise form:

$$18.0 \text{ g } H_2O = 2.0 \text{ g H} + 16.0 \text{ g O}$$

Mass relationships such as above mentioned allow percent compositions to be calculated easily.

Example 2.11 Mass Percentage Calculations

The human body makes ammonia (NH_3) when proteins are broken down, then converting that ammonia into urea. Calculate the mass percentage of nitrogen (N) in ammonia.

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: ammonia is NH_3

Unknown: mass % of N = ?

STEP 2 Identify a formula that links the given and unknown terms.

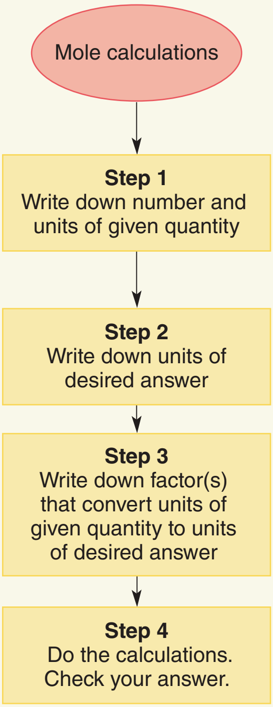
Key Equation 1.6: $\% = \frac{\text{part}}{\text{total}} \times 100$

STUDY TOOLS 2.1

Help with Mole Calculations

Problems involving the use of the mole often strike fear initially into the hearts of chemistry students. The good news is that problems involving the use of moles, atoms, molecules, and grams are made easier by using the factor-unit method. This method focuses your attention on the goal of eliminating the unit of the known, or given quantity, and to generate the unit of the answer, or unknown quantity. Remember, Step 1 is to write down the number and unit of the given quantity. In Step 2, write down the unit of the answer. In Step 3, multiply the known quantity by a factor whose units will cancel out the units of the known quantity and will generate the unit of the answer. In Step 4, obtain the answer by doing the required arithmetic using the numbers that were introduced in Steps 1–3. Remember, anytime you see the word *moles*, think of the factor-unit method.

The steps given in the flow chart below will help you out in resolving the problems.


Mole calculations
Step 1
Write down number and units of given quantity
Step 2
Write down units of desired answer
Step 3
Write down factor(s) that convert units of given quantity to units of desired answer
Step 4
Do the calculations. Check your answer.

STEP 3 Enter the data into the formula.

We will use 1 mol of each compound as a sample, because the mass in grams of 1 mol of compound and the mass in grams of N in the 1 mol of compound are readily determined. One mol of NH_3 weighs 17.0 g and contains 1 mol of N atoms, which weighs 14.0 g.

$$\%\ \mathrm{N} = \frac{14.0\ \mathrm{g}}{17.0\ \mathrm{g}} \times 100 = 82.4\%$$

STEP 4 Check to see whether the answer makes sense.

Yes. Nitrogen should contribute the majority of mass in NH_3.

✔ **LEARNING CHECK 2.10** Determine the mass percentage of carbon in carbon dioxide (CO_2) and carbon monoxide (CO).

Environmental Career Description

WILDLIFE TECHNICIAN FOLLOW-UP

Wildlife technicians must be educated in biology and should be able to endure the rigors of fieldwork, including, hiking, lifting, wading, enduring harsh weather conditions, and operating equipment and machinery such as tractors and trailers.

A Division of Natural Resources (DNR) job announcement for a wildlife technician reads, "The incumbent is responsible for fish propagation to include feeding fish, cleaning raceways, ponds, and other water management structures, will assist in spawning, egg picking, receiving and egg disinfection operations, learning and assisting with necropsies of various sport fish groups and gather daily, weekly, and monthly biological data. Additional duties include maintenance of buildings, grounds and trails; grounds keeping work; performing other duties as assigned." The job posting also states that preference will be given to individuals seeking a bachelor's degree, or those who already have a bachelor's degree.

Wildlife technician work tends to be seasonal. If the work occurs in remote areas, housing may be provided. Students earning bachelor or master's degrees in biological sciences often apply for these seasonal jobs. The majority of wildlife technician work is available through state and federal government postings (e.g., USAJobs.gov).

Concept Summary

2.1 Symbols and Formulas

Learning Objective: Can you use symbols for chemical elements to write formulas for chemical compounds?

- Symbols based on names have been assigned to every element.
- Most elements consist of a single capital letter followed by a lowercase letter.
- A few elements consist of a single capital letter.
- Compounds are represented by formulas made up of elemental symbols.
- The number of atoms of each element in a molecule is shown by subscripts.

2.2 Inside the Atom

Learning Objective: Can you identify the characteristics of protons, neutrons, and electrons?

- Atoms are made up of numerous smaller particles.
- These smaller particles are the protons, neutrons, and electrons, and they are most important to chemical studies.
- Positively charged protons and neutral neutrons have a relative mass of 1 u each and are located in the nuclei of atoms.
- Negatively charged electrons with a mass of 1/1836 u are located outside the nuclei of atoms.

2.3 Isotopes

Learning Objective: Can you use the concepts of atomic number and mass number to determine the number of subatomic particles in isotopes and to write correct symbols for isotopes?

- Most elements in their natural state are made up of more than one kind of atoms.
- These different kinds of atoms of a specific element are called isotopes.
- They differ from one another only in the number of neutrons in their nuclei.
- A symbol incorporating atomic number, mass number, and elemental symbol is used to represent a specific isotope.

2.4 Relative Masses of Atoms and Molecules

Learning Objective: Can you use atomic weights of the elements to calculate molecular weights of compounds?

- Relative masses called atomic weights have been assigned to each element and are tabulated in the periodic table.
- The units used are atomic mass units, abbreviated u.
- Relative masses for molecules, called molecular weights, are determined by adding the atomic weights of the atoms making up the molecules.

2.5 Isotopes and Atomic Weights

Learning Objective: Can you use isotope percent abundances and masses to calculate atomic weights of elements?

- The atomic weights measured for elements are average weights that depend on the percentages and masses of the isotopes in the naturally occurring element.
- If the isotope percent abundances and isotope masses are known for an element, its atomic weight can be calculated.

2.6 Avogadro's Number: The Mole

Learning Objective: Can you use the mole concept to obtain relationships between the number of moles, number of grams, and number of atoms for elements and use those relationships to obtain factors for use in factor-unit calculations?

- Avogadro's number of the atoms of an element has a mass in grams equal to the atomic weight of the element.
- Avogadro's number of molecules has a mass in grams equal to the molecular weight.
- Avogadro's number of particles is called a mole, abbreviated mol.

2.7 The Mole and Chemical Formulas

Learning Objective: Can you use the mole concept and molecular formulas to obtain relationships between the number of moles, number of grams, and number of atoms or molecules for compounds and use those relationships to obtain factors for use in factor-unit calculations?

- When applied to molecular formulas, the mole concept gives numerous relationships that yield useful factors for factor-unit calculations.

Key Terms and Concepts

Atomic mass unit (u) (2.4)
Atomic number of an atom (2.3)
Atomic weight (2.4)
Compound formula (2.1)
Elemental symbol (2.1)
Isotopes (2.3)
Mass number of an atom (2.3)
Mole (2.6)
Molecular weight (2.4)
Nucleus (2.2)

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

You will find it useful to refer to **Table 2.1** and the periodic table inside the front cover as you work through these exercises.

Symbols and Formulas (Section 2.1)

2.1 Draw a "formula" for each of the following molecules using circular symbols of your choice to represent atoms:

- **a.** A diatomic molecule of an element
- **b.** A diatomic molecule of a compound
- **c.** A triatomic molecule of an element
- **d.** A molecule of a compound containing one atom of one element and four atoms of another element

2.2 Draw a "formula" for each of the following molecules using circular symbols of your choice to represent atoms:

- **a.** A triatomic molecule of a compound
- **b.** A molecule of a compound containing two atoms of one element and two atoms of a second element
- **c.** A molecule of a compound containing two atoms of one element, one atom of a second element, and four atoms of a third element
- **d.** A molecule containing two atoms of one element, six atoms of a second element, and one atom of a third element

2.3 Write formulas for the following molecules using elemental symbols from **Table 2.1** and subscripts. Compare these formulas with those in Exercise 2.1.

- **a.** A diatomic molecule of chlorine gas
- **b.** A diatomic molecule of hydrogen fluoride (one hydrogen atom and one fluorine atom)
- **c.** A triatomic molecule of ozone (a molecular form of the element oxygen)
- **d.** A molecule of carbon tetrachloride (one atom of carbon and four atoms of chlorine)

2.4 Write formulas for the following molecules using elemental symbols from **Table 2.1** and subscripts. Compare these formulas with those in Exercise 2.2.

- **a.** A molecule of water (two hydrogen atoms and one oxygen atom)
- **b.** A molecule of hydrogen peroxide (two hydrogen atoms and two oxygen atoms)
- **c.** A molecule of sulfuric acid (two hydrogen atoms, one sulfur atom, and four oxygen atoms)
- **d.** A molecule of ethyl alcohol (two carbon atoms, six hydrogen atoms, and one oxygen atom)

2.5 Determine the number of each type of atom in molecules represented by the following formulas:

- **a.** ammonia (NH_3)
- **b.** acetic acid ($C_2H_4O_2$)
- **c.** boric acid (H_3BO_3)
- **d.** ethane (C_2H_6)

2.6 Determine the number of each type of atom in molecules represented by the following formulas:

- **a.** sulfur dioxide (SO_2)
- **b.** butane (C_4H_{10})
- **c.** chlorous acid ($HClO_2$)
- **d.** boron trifluoride (BF_3)

2.7 Tell what is wrong with each of the following molecular formulas and write a correct formula:

- **a.** H_3PO_3 (phosphorous acid)
- **b.** $SICI_4$ (silicon tetrachloride)
- **c.** SOO (sulfur dioxide)
- **d.** 2HO (hydrogen peroxide—two hydrogen atoms and two oxygen atoms)

2.8 Tell what is wrong with each of the following formulas and write a correct formula:

- **a.** HSH (hydrogen sulfide)
- **b.** $HCLO_2$ (chlorous acid)
- **c.** $2HN_2$ (hydrazine—two hydrogen atoms and four nitrogen atoms)
- **d.** C2H6 (ethane)

Inside the Atom (Section 2.2)

2.9 Determine the charge and mass (in u) of nuclei made up of for the following particles:

- **a.** 6 protons and 6 neutrons
- **b.** 8 protons and 9 neutrons
- **c.** 20 protons and 25 neutrons
- **d.** 52 protons and 78 neutrons

2.10 Determine the charge and mass (in u) of nuclei made up of the following particles:

- **a.** 4 protons and 5 neutrons
- **b.** 9 protons and 10 neutrons
- **c.** 20 protons and 23 neutrons
- **d.** 47 protons and 60 neutrons

2.11 Determine the number of electrons that would have to be associated with each nucleus described in Exercise 2.9 to produce a neutral atom.

2.12 Determine the number of electrons that would have been associated with each nucleus described in Exercise 2.10 to produce a neutral atom.

Isotopes (Section 2.3)

2.13 Determine the number of electrons and protons contained in an atom of the following elements:

- **a.** sulfur
- **b.** As
- **c.** element number 24

2.14 Determine the number of electrons and protons contained in an atom of the following elements:

- **a.** silicon
- **b.** Sn
- **c.** element number 74

2.15 Determine the number of protons, number of neutrons, and number of electrons in atoms of the following isotopes:

- **a.** ${}^{3}_{2}He$
- **b.** ${}^{9}_{4}Be$
- **c.** ${}^{235}_{92}U$

2.16 Determine the number of protons, number of neutrons, and number of electrons in atoms of the following isotopes:

- **a.** ${}^{34}_{16}S$
- **b.** ${}^{91}_{40}Zr$
- **c.** ${}^{131}_{54}Xe$

2.17 Write symbols like those given in Exercises 2.15 and 2.16 for the following isotopes:

- **a.** cadmium-110
- **b.** cobalt-60
- **c.** uranium-235

2.18 Write symbols like those given in Exercises 2.15 and 2.16 for the following isotopes:

- **a.** silicon-28
- **b.** argon-40
- **c.** strontium-88

2.19 Determine the mass number and atomic number for atoms containing the nuclei described in Exercise 2.9. Write symbols for each atom like those given in Exercises 2.15 and 2.16.

2.20 Determine the mass number and atomic number for neutral atoms containing the nuclei described in Exercise 2.10. Write symbols for each atom like those given in Exercises 2.15 and 2.16.

2.21 Write isotope symbols for neutral atoms with the following characteristics:

- **a.** Contains 20 electrons and 20 neutrons
- **b.** Contains 1 electron and 2 neutrons
- **c.** A magnesium atom that contains 14 neutrons

2.22 Write isotope symbols for neutral atoms with the following characteristics:

- **a.** Contains 17 electrons and 20 neutrons
- **b.** A copper atom with a mass number of 65
- **c.** A zinc atom that contains 36 neutrons

Relative Masses of Atoms and Molecules (Section 2.4)

2.23 Write the symbols and names for two elements whose average atoms have masses that are within 0.3 u of each other. Don't look beyond element number 83.

2.24 Round atomic weights to the nearest whole number, and determine how many helium atoms would balance one carbon atom on a seesaw.

2.25 Round atomic weights to the nearest whole number, and determine how many lithium atoms would balance two nitrogen atoms on a seesaw.

2.26 What are the symbol and name for an element whose average atoms have a mass that is 77.1% of the mass of an average chromium atom?

2.27 In the first 36 elements, 6 elements have atoms whose average mass is within 0.2 u of being twice the atomic number of the element. Write the symbols and names for these 6 elements.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

2.28 What are the symbol and name of the element whose average atoms have a mass very nearly half the mass of an average silicon atom?

2.29 Determine the molecular weights in u of the following compounds used as dietary mineral supplements:

a. $Ca_3C_{12}H_{10}O_{14}$ (calcium citrate, source of calcium)

b. $CuSO_4$ (copper sulfate, source of copper)

c. KI (potassium iodide, source of iodine)

d. $MnCl_2$ (manganese chloride, source of manganese)

2.30 Determine the molecular weights in u of the following compounds used as dietary mineral supplements:

a. $CaCO_3$ (calcium carbonate, source of calcium)

b. $C_4H_2FeO_4$ (ferrous fumarate, source of iron)

c. $MgSO_4$ (magnesium sulfate, source of magnesium)

d. $C_4H_6O_4Zn$ (zinc acetate, source of zinc)

2.31 The molecular weight was determined for a gas that is known to be an oxide of nitrogen. The value obtained experimentally was 43.98 u. Which of the following is most likely to be the formula of the gas? NO, N_2O, NO_2.

2.32 A flammable gas is known to contain only carbon and hydrogen. Its molecular weight is determined and found to be 28.05 u. Which of the following is likely the identity of the gas? Acetylene (C_2H_2), ethylene (C_2H_4), ethane (C_2H_6).

2.33 Glycine, an amino acid found in proteins, has a molecular weight of 75.07 u and is represented by the formula $C_2H_xNO_2$. What number does x stand for in the formula?

2.34 Serine, an amino acid found in proteins, has a molecular weight of 105.10 u and is represented by the formula $C_yH_7NO_3$. What number does y stand for in the formula?

Isotopes and Atomic Weights (Section 2.5)

2.35 Naturally occurring sodium has a single isotope. Determine the following for the naturally occurring atoms of sodium:

a. The number of neutrons in the nucleus

b. The mass (in u) of the nucleus (to three significant figures)

2.36 Naturally occurring aluminum has a single isotope. Determine the following for the naturally occurring atoms of aluminum:

a. The number of neutrons in the nucleus

b. The mass (in u) of the nucleus (to three significant figures)

2.37 Calculate the atomic weight of lithium on the basis of the following percent composition and atomic weights of the naturally occurring isotopes. Compare the calculated value with the atomic weight listed for lithium in the periodic table.

lithium-6 = 7.42% (6.0151 u)
lithium-7 = 92.58% (7.0160 u)

2.38 Calculate the atomic weight of boron on the basis of the following percent composition and atomic weights of the naturally occurring isotopes. Compare the calculated value with the atomic weight listed for boron in the periodic table.

boron-10 = 19.78% (10.0129 u)
boron-11 = 80.22% (11.0093 u)

2.39 Calculate the atomic weight of silicon on the basis of the following percent composition and atomic weights of the naturally occurring isotopes. Compare the calculated value with the atomic weight listed for silicon in the periodic table.

silicon-28 = 92.21% (27.9769 u)
silicon-29 = 4.70% (28.9765 u)
silicon-30 = 3.09% (29.9738 u)

2.40 Calculate the atomic weight of copper on the basis of the following percent composition and atomic weights of the naturally occurring isotopes. Compare the calculated value with the atomic weight listed for copper in the periodic table.

copper-63 = 69.09% (62.9298 u)
copper-65 = 30.91% (64.9278 u)

Avogadro's Number: The Mole (Section 2.6)

2.41 Refer to the periodic table and determine how many grams of sulfur contain the same number of atoms as 3.10 grams of phosphorus.

2.42 Refer to the periodic table and determine how many grams of fluorine contain the same number of atoms as 1.60 g of oxygen.

2.43 Write three relationships (equalities) based on the mole concept for each of the following elements:

a. beryllium

b. lead

c. sodium

2.44 Write three relationships (equalities) based on the mole concept for each of the following elements:

a. phosphorus

b. aluminum

c. krypton

2.45 Use a factor derived from the relationships written in Exercise 2.43 and the factor-unit method to determine the following:

a. The number of moles of beryllium atoms in a 10.0 g sample of beryllium

b. The number of lead atoms in a 2.00 mol sample of lead

c. The number of sodium atoms in a 50.0 g sample of sodium

2.46 Use a factor derived from the relationships written in Exercise 2.44 and the factor-unit method to determine the following:

a. The mass in grams of one phosphorus atom

b. The number of grams of aluminum in 1.65 mol of aluminum

c. The total mass in grams of one-fourth Avogadro's number of krypton atoms

The Mole and Chemical Formulas (Section 2.7)

2.47 Refer to the periodic table and calculate the molecular weights for the compounds PH_3 and SO_2. Then determine how many grams of PH_3 contain the same number of molecules as 6.41 g of SO_2.

2.48 Refer to the periodic table and calculate the molecular weights for the compounds BF_3 and H_2S. Then, determine how many grams of BF_3 contain the same number of molecules as 0.34 g of H_2S.

2.49 For each formula given below, write statements equivalent to Statements 1–6 (see **Section 2.7**):

- **a.** CO_2, carbon dioxide, aerobic respiration product
- **b.** $C_3H_6O_3$, lactic acid, anaerobic respiration product
- **c.** $C_6H_{12}O_6$, glucose, respiration energy source

2.50 For each general anesthetic formula given below, write statements equivalent to Statements 1–6 (see **Section 2.7**):

- **a.** C_2H_6O, ethyl alcohol (whiskey)
- **b.** $C_4H_{10}O$, ethyl ether (flammable)
- **c.** $C_2HBrClF_3$, halothane (nonflammable)

2.51 Answer the following questions based on information contained in the statements you wrote for Exercise 2.49.

- **a.** How many moles of oxygen atoms are contained in 1 mol of CO_2 molecules?
- **b.** How many grams of carbon are contained in 1.00 mol of $C_3H_6O_3$?
- **c.** What is the mass percentage of oxygen in $C_6H_{12}O_6$?

2.52 Answer the following questions based on information contained in the statements you wrote for Exercise 2.50.

- **a.** How many carbon atoms are contained in 0.25 mol of C_2H_6O?
- **b.** How many moles of hydrogen atoms are contained in 0.50 mol of ethyl ether?
- **c.** How many grams of hydrogen are contained in 2.00 mol of halothane?

2.53 An intravenous solution of normal saline may contain 1.70 mol of sodium chloride (NaCl). How many sodium atoms are present in the solution?

2.54 If an adult woman has a mass of 60.0 kg and contains 0.00172% iron, how many moles of iron are in her body?

2.55 Determine the mass percentage of carbon in CO and CO_2.

2.56 Determine the mass percentage of hydrogen in CH_4 and C_2H_6.

2.57* Any of the statements based on a mole of substance (Statements 4–6) can be used to obtain factors for problem solving by the factor-unit method. Write statements equivalent to 4, 5, and 6 for nitrophenol ($C_6H_5NO_3$). Use a single factor obtained from the statements to solve each of the following. A different factor will be needed in each case.

- **a.** How many grams of nitrogen are contained in 70.0 g of $C_6H_5NO_3$?
- **b.** How many moles of oxygen atoms are contained in 1.50 mol of $C_6H_5NO_3$?
- **c.** How many atoms of carbon are contained in 9.00×10^{22} molecules of $C_6H_5NO_3$?

2.58 Any of the statements based on a mole of substance (Statements 4–6) can be used to obtain factors for problem solving by the factor-unit method. Write statements equivalent to 4, 5, and 6 for fructose ($C_6H_{12}O_6$). Use a single factor obtained from the statements to solve each of the following. A different factor will be needed in each case.

- **a.** How many grams of oxygen are contained in 43.5 g of $C_6H_{12}O_6$?
- **b.** How many moles of hydrogen atoms are contained in 1.50 mol of $C_6H_{12}O_6$?
- **c.** How many atoms of carbon are contained in 7.50×10^{22} molecules of $C_6H_{12}O_6$?

2.59 Urea (CH_4N_2O) and ammonium sulfate ($N_2H_8SO_4$) are both used as agricultural fertilizers. Which one contains the higher mass percentage of nitrogen?

2.60 What is the mass in grams of 6.40×10^{-3} mol of the hormone epinephrine ($C_9H_{13}NO_3$)?

2.61 Cortisone ($C_{21}H_{28}O_5$) is used as an antiinflammatory drug. How many moles of cortisone are present in one 10.0 mg tablet?

Additional Exercises

2.62 The two major isotopes of uranium metal found in nature are U-235 and U-238. Which isotope has the greater density? Explain your reasoning.

2.63 About one billion (1.0×10^9) peas can fit into a railroad car. What percentage of one mole of peas is this number?

2.64 The mass of a single carbon-12 atom is 1.99×10^{-23} g. What is the mass in grams of a single carbon-14 atom?

2.65 One mole of water molecules, H_2O, has a mass of 18.0 g. What would be the mass in grams of one mole of heavy water molecules, D_2O, where D represents the isotope?

2.66 According to the caption of **Figure 2.4**, atoms are composed primarily of empty space (99.999% empty). What would happen to the density of matter (increase or decrease) if the electrons were actually located at the distance from the nucleus shown in the atom drawing of **Figure 2.4**? Explain your reasoning.

Chemistry for Thought

2.67 **a.** Explain how atoms of different elements differ from one another.

- **b.** Explain how atoms of different isotopes of the same element differ from one another.

2.68 The atomic weight of aluminum is 26.98 u, and the atomic weight of nickel is 58.69 u. All aluminum atoms have a mass of 26.98 u, but not a single atom of nickel has a mass of 58.69 u. Explain.

2.69 Answer the question in the caption of **Figure 2.8** (see page 57). Would you expect any orange in the bowl to have the exact mass you calculated as an average? Explain.

Even-numbered exercises answered in Appendix B.
Exercises with an asterisk (*) are more challenging.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

2.70 Answer the question in the caption of **Figure 2.11**. Use your answer and the fact that an average jelly bean has a mass of 1.18 g to calculate the number of beans in each jar.

2.71 Answer the question in the caption of **Figure 2.14**. How many CS_2 molecules would be required to contain 0.25 mol of sulfur atoms?

2.72 In **Section 2.4**, it was pointed out that an atomic mass unit, u, is equal to $\frac{1}{12}$ of the mass of an atom of carbon-12. Suppose one atomic mass unit was redefined as being equal to $\frac{1}{24}$ of the mass of a carbon-12 atom. How would this change influence the value of the atomic weight of magnesium?

2.73 How would the change of question 2.72 influence the ratio of the atomic weight of magnesium divided by the atomic weight of hydrogen?

2.74 How would the change of question 2.72 influence the value of Avogadro's number?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

3 Electronic Structure and the Periodic Law

kali9/E+/Getty Images

Health Career Focus

RADIOLOGIC TECHNICIAN/RADIOLOGIST

My mom used to say I'd better get a job with medical insurance because I spent so much time at the ER! Between snowboarding, skateboarding, rock climbing, and competition soccer, I must have had a scan or X-ray of every bone in my body. The images captivated me. I knew early that radiology was the career for me.

My radiology program was highly competitive. Most successful applicants maintained a 3.75 GPA or higher. I didn't mind, because I'm tenacious. I brought the same competitive spirit from sports and applied it to academics. If I didn't earn the grade I needed, I immediately registered to repeat the class, found a tutor, and studied harder.

I like my job. It's interesting, it has good benefits, and I get to work with people of all ages in varied circumstances, from accidents to arthritis. I still snowboard on my days off, but now I'm on the right side of the camera!

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Sources: Explore Health Careers. Retrieved from https://explorehealthcareers.org/career/allied-health-professions/radiologic-technologist/Johns Hopkins Intrastaff Radiology Technician. Retrieved from https://www.linkedin.com/jobs/view/radiology-technician-night-shift-at-johns-hopkins-intrastaff-1653436292?utm_campaign=google_jobs_apply&utm_source=google_jobs_apply&utm_medium=organic

Learning Objectives

When you complete your study of this chapter, you should be able to:

1. Locate elements in the periodic table on the basis of group and period designations. **(Section 3.1)**
2. Determine the number of electrons in designated atomic orbitals, subshells, or shells. **(Section 3.2)**
3. Determine the number of valence shell electrons and the electronic structure for atoms, and relate this information to the location of elements in the periodic table. **(Section 3.3)**
4. Determine the following for elements: the electronic configuration of atoms, the number of unpaired electrons in atoms, and the identity of atoms based on provided electronic configurations. **(Section 3.4)**

5 Determine the shell and subshell locations of the distinguishing electrons in elements, and based on their location in the periodic table, classify elements into the categories given in **Figures 3.13** and **3.16**. **(Section 3.5)**

6 Recognize property trends of elements within the periodic table, and use the trends to predict selected properties of the elements. **(Section 3.6)**

IN CHAPTER 1, we defined atoms as particles that represent the limit of chemical subdivision. According to this idea, atoms of a specific element can neither be divided into smaller particles nor can be converted into atoms of another element by any physical or chemical change. Then in Chapter 2, we introduced the idea that atoms are, in fact, made up of particles that are smaller than the atoms themselves. Two of these particles, protons and neutrons, form the nuclei of atoms, whereas electrons are located outside the nuclei.

The idea that atoms are made up of subatomic particles implies that it should be possible to obtain even smaller particles from atoms. Scientists have found that it is possible to transfer electrons from one atom to another atom or can be shared between atoms during a chemical change. Some details of these processes are given in Chapter 4, but it is known that the transfer of electrons depends on the arrangement of the electrons around the nuclei of atoms. These electronic arrangements are one of the major topics of this chapter.

World History Archive/Alamy Stock Photo

FIGURE 3.1 Dimitri Mendeleev organized the elements into a classification scheme in 1869.

3.1 The Periodic Law and Table

Learning Objective 1 Locate elements in the periodic table on the basis of group and period designations.

By the early 19th century, detailed studies of the elements known at that time had produced an abundance of chemical information. Scientists looked for order in these facts, with the hope of providing a systematic approach to the study of chemistry. Two scientists independently, and almost simultaneously, made the same important contribution to this end. Julius Lothar Meyer, a German, and Dimitri Mendeleev (see **Figure 3.1**), a Russian, each produced classification schemes separately for the elements in 1869. Both schemes were based on the **periodic law**, which in its present form is stated as follows: When all the elements are arranged in order of increasing atomic numbers, elements with similar chemical properties will occur at regular (periodic) intervals.

periodic law A statement about the behavior of the elements when they are arranged in a specific order. In its present form, it is stated as follows: Elements with similar chemical properties occur at regular (periodic) intervals when the elements are arranged in order of increasing atomic numbers.

A convenient way to compactly represent such behavior is to use tables. The arrangement of the elements in a table based on the periodic law is called a *periodic table*. In modern periodic table, such as the one inside the front cover of this book, elements with similar chemical properties are found in vertical columns called **groups** or **families**.

group or family of the periodic table A vertical column of elements that have similar chemical properties.

In this book, the groups are designated in two ways. In the U.S. system, a Roman numeral and letter, such as IIA, is used. In the International Union of Pure and Applied Chemistry system, a simple number, such as 2, is used. Both designations appear on the periodic table inside the front cover of this book, with the IUPAC number in parentheses. We will generally refer to groups in the text by using both the U.S. system and the IUPAC system. Thus, a reference to the second group would be given as group IIA(2), where we have put the IUPAC number in parentheses. The horizontal rows in the table are called **periods** and are numbered from top to bottom. Thus, each element belongs to both a period and a group of the periodic table.

period of the periodic table A horizontal row of elements.

Example 3.1 Groups and Periods of the Periodic Table

Phosphorus (P) is an essential element for the formation of bones and teeth. Chromium (Cr) is also an essential element which helps the body to utilize glucose.

Identify the group and period to which each of the following belongs:

a. P b. Cr c. element number 30 d. element number 53

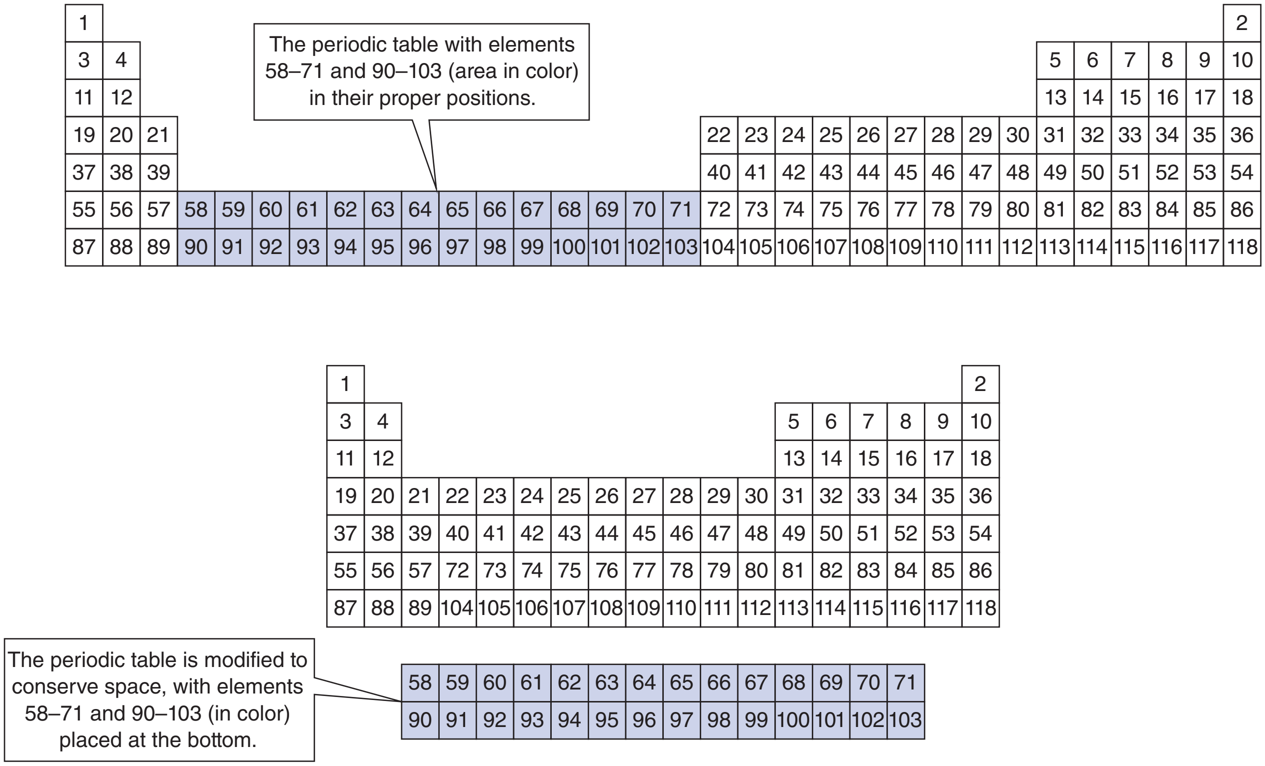
Solution

a. Phosphorus (P) is present in group VA(15) and period 3.
b. Chromium (Cr) is in group VIB(6) and period 4.
c. The element with atomic number 30 is zinc (Zn), which is found in group IIB(12) and period 4.
d. Element number 53 is iodine (I), found in group VIIA(17) and period 5.

✔ **LEARNING CHECK 3.1** Write the symbol for the element found in the following places of the periodic table:

a. Group IVA(14) and period 4 b. Group VIIB(7) and period 6

It should be noted that the periodic table as given inside the front cover appears to violate the practice of arranging the elements according to increasing atomic number. Element 72 follows element 57, and 104 follows 89, whereas elements 58–71 and 90–103 are arranged in two rows at the bottom of the table. Technically, these two rows should be included in the body of the table as shown in **Figure 3.2** (top). To save horizontal space, they are placed in the position shown in **Figure 3.2** (bottom). This exception presents no problem, as long as it is understood.



The periodic table with elements 58–71 and 90–103 (area in color) in their proper positions.

The periodic table is modified to conserve space, with elements 58–71 and 90–103 (in color) placed at the bottom.

FIGURE 3.2 Forms of the periodic table.

Example 3.2 More Groups and Periods of the Periodic Table

a. How many elements are found in period 6 of the periodic table?
b. How many elements are found in group VA(15) of the periodic table?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Solution

a. Period 6 includes elements 55–86, even though elements 58–71 are shown below the main table. Therefore, period 6 contains 32 elements.
b. A count shows group VA(15) contains 6 elements: N, P, As, Sb, Bi, and number 115.

✔ **LEARNING CHECK 3.2** How many elements are found in the following?
a. Period 1 of the periodic table
b. Group IIB(12) of the periodic table.

3.2 Electronic Arrangements in Atoms

Learning Objective 2 Determine the number of electrons in designated atomic orbitals, subshells, or shells.

In 1913 Niels Bohr, a young Danish physicist, made an important contribution to understand more about atomic structure. He was working under the direction of Ernest Rutherford, a British scientist, who had proposed a solar system model for atoms in which negative electrons moved in circular orbits around the positive nucleus, much like the planets move around the sun. Based of this model, Bohr proposes a new model by suggesting that the single electron of a hydrogen atom could occupy orbits only at specific distances from the nucleus, and thus the electron could have only specific energies (see **Figure 3.3**). Bohr further proposed that the electron change orbits only by absorbing or releasing energy. The addition of energy to a hydrogen atom elevated the electron to a higher-energy orbit located farther from the nucleus. The energy released when an electron dropped from a higher- to a lower-energy orbit appeared as emitted light.

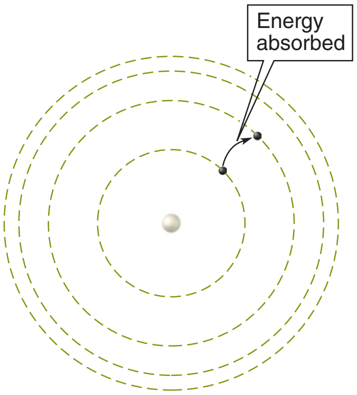


FIGURE 3.3 A diagram of the Bohr hydrogen atom (not drawn to scale; the orbits are actually much larger than the nucleus). The electron is elevated to a higher-energy orbit when energy is absorbed.

Research in the nature of atoms continued after Bohr's proposal, and in 1926 a revised model of atomic structure was proposed by Erwin Schrödinger, an Austrian physicist, who received the Nobel Prize in physics in 1933 in recognition of this achievement. According to Schrödinger's quantum mechanical model, the precise paths of electrons cannot be determined accurately, as Bohr's model proposed. It was found that the location and energy of electrons around a nucleus can be specified using three terms: shell, subshell, and orbital. This is somewhat like locating an individual in a city by specifying a street, building, and apartment.

shell A location and energy of electrons around a nucleus is designated by a value for *n*, where *n* = 1, 2, 3, etc.

The location of electrons in a **shell** is indicated by assigning a number, *n*, to the shell and to all the electrons within the shell. The *n* value of the lowest-energy shell is 1, that of the next higher energy is 2, the next is 3, and so on. Higher *n* values for a shell correspond to higher energies and greater distances from the nucleus for the electrons of the shell. Electrons in the third shell all have an *n* value of 3, all have an energy higher than the energies of electrons in shells 1 and 2, and also are located farther from the nucleus than those in shells 1 and 2.

subshell A component of a shell that is designated by a letter representing the group *s*, *p*, *d*, and *f*.

Each shell is made up of **subshells** that are designated by a letter representing the group *s*, *p*, *d*, and *f*. Because all subshells are designated by one of these letters regardless of the shell in which the subshell is found, a combination of both shell number and subshell letter is used to identify subshells clearly. Thus, a *p* subshell in shell number 2 is referred to as a 2*p* subshell. The number of subshells found in a shell is the same as the value of *n* for the shell. Thus, shell number 2 ($n = 2$) contains two subshells. The subshells are the 2*p* mentioned earlier and 2*s*. Electrons located in specific subshells are often referred to in terms of the same number and letter as the subshell. For example, we might refer to an atom as having three 2*p* electrons. All electrons within a specific subshell have the same energy.

atomic orbital A volume of space around atomic nuclei in which electrons of the same energy move. Groups of orbitals with the same *n* value form subshells.

The description of the location and energy of electrons moving around a nucleus is completed in the quantum mechanical model by specifying an orbital. Each subshell consists of one or more **atomic orbitals**, which are specific volumes of space around nuclei in which electrons move. These atomic orbitals must not be confused with the fixed electronic orbits of the original Bohr theory; they are *not* the same. These volumes of space around nuclei have different shapes, depending on the energy of the electrons they contain

HEALTH CONNECTIONS 3.1

Watch the Salt

An average adult in the United States consumes about 3400 milligrams of sodium each day in the form of table salt. Only about one in ten Americans meets the recommended daily limit by the American Heart Association of 2300 milligrams of sodium. The overconsumption of sodium increases the risk of developing high blood pressure, a leading cause of cardiovascular disease that, in turn, accounts for two-thirds of all strokes and half of the heart disease in the United States.

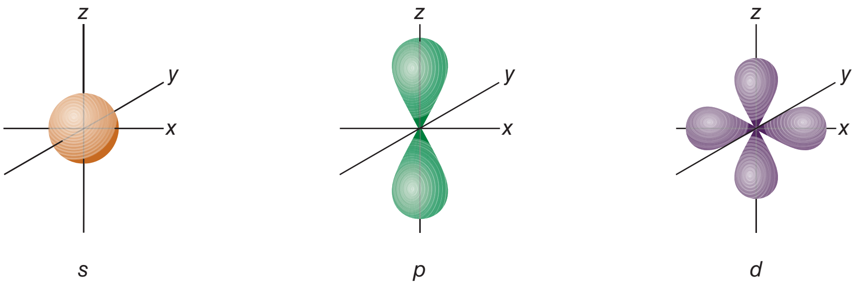
Salt is often present in processed and prepared foods such as pizza, bread, cold cuts, and sandwiches. A fast-food breakfast sandwich can contain as much as 50% of the recommended daily limit of salt in one food item alone. Make it a practice to read labels of items you buy at the grocery store. When you eat at home, be aware of the amount of salt you use.

Increase the amount of potassium in your diet: bananas, yogurt, baked potatoes, salmon, and avocado are among the tasty foods rich in potassium. Dietary potassium helps relax blood vessels, decreases blood pressure, and helps eliminate excess sodium from your body.

Salt is often present in processed foods such as pizza, bread, and cold cuts.

(see **Figure 3.4**). All *s* subshells consist of a single orbital that is also designated by the letter *s* and further identified by the *n* value of the shell to which the subshell belongs. Thus, the 2*s* subshell mentioned earlier consists of a single 2*s* orbital. All *p* subshells consist of three *p* orbitals that also carry the *n* value of the shell. Thus, the 2*p* subshell of shell number 2 consists of three 2*p* orbitals. Since all the electrons in a subshell have the same energy, an electron in any one of the three 2*p* orbitals has the same energy, regardless of which orbital of the three it occupies. All *d* subshells contain five orbitals, and all *f* subshells contain seven orbitals. According to the quantum mechanical model, each orbital within a subshell can contain a maximum of two electrons.

FIGURE 3.4 Shapes of typical *s*, *p*, and *d* orbitals.



The shapes of orbitals such as those given in **Figure 3.4** must not be interpreted incorrectly. The fact that *s* orbitals are spherical in shape does not mean that the electrons move around on the spherical surface. According to the quantum mechanical model, electrons in *s* orbitals move within the spherical volume of the orbital in paths that cannot be determined. All that can be determined about their behavior within the orbital is the probability of finding them in a specific location, which is what **Figure 3.4** depicts. Thus, if it were determined that an electron had a 2% probability of being at a specific location, it would simply mean that the electron could be found at that location within an orbital 2 times out of every 100 times we looked for it there. Similarly, electrons in *p* or *d* orbitals do not move on the surface of the dumbbell- or cloverleaf-shaped orbitals; they move *within* the three-dimensional dumbbell- or cloverleaf-shaped volumes.

The energy of electrons located in an orbital within a subshell and shell is determined by two factors. As mentioned earlier, the higher the value of *n*, the higher the energy. In addition, if *n* is the same, but the subshell is different, the energy of the electrons increases in the order *s*, *p*, *d*, *f*. Thus, a 3*p* electron (an electron in a 3*p* subshell) has a higher energy than a 3*s* electron (an electron in a 3*s* subshell). **Figure 3.5** is a diagrammatic representation of the fourth shell of an atom completely filled with electrons.

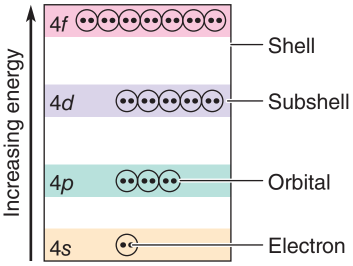


FIGURE 3.5 The fourth shell of an atom, completely filled with electrons.

Example 3.3 Shells and Subshells of Atoms

Determine the following for the third shell of an atom:

a. The number of subshells
b. The designation for each subshell
c. The number of orbitals in each subshell
d. The maximum number of electrons that can be contained in each subshell
e. The maximum number of electrons that can be contained in the shell

Solution

a. The number of subshells is the same as the number used to designate the shell. Therefore, the third shell contains three subshells.
b. Subshells increase in energy according to the order *s*, *p*, *d*, *f*. The subshells in the shell are therefore designated 3*s*, 3*p*, and 3*d*.
c. The number of orbitals in the subshells is 1, 3, and 5 because *s* subshells always contain a single orbital, *p* subshells always contain three orbitals, and *d* subshells always contain five orbitals.
d. Each atomic orbital can contain a maximum of two electrons, independent of the type of orbital under discussion. Therefore, the 3*s* subshell (one orbital) can hold a maximum of two electrons, the 3*p* subshell (three orbitals) can hold a maximum of 6 electrons, and the 3*d* subshell (five orbitals) a maximum of 10 electrons.
e. The maximum number of electrons that can be contained in the shell is simply the sum of the maximum number of electrons in each subshell, $2 + 6 + 10 = 18$.

✔ LEARNING CHECK 3.3 In each of the following, what is the maximum number of electrons that can be found?

a. 4*p* orbital b. 5*d* subshell c. shell number 1

It might seem to you at this point that the modifications to the Bohr theory have created a number of hard-to-remember relationships between shells, subshells, orbitals, and electrons. However, some patterns help to make the relationships easy to remember. **Table 3.1** summarizes them for the first four shells of an atom.

TABLE 3.1 Relationships between Shells, Subshells, Orbitals, and Electrons

Shell Number (*n*)	Number of Subshells in Shell	Subshell Designation	Number of Orbitals in Subshell	Orbital Designation	Maximum Number of Electrons in Subshell	Maximum Number of Electrons in Shell
1	1	1*s*	1	1*s*	2	2
2	2	2*s*	1	2*s*	2	
		2*p*	3	$2p(2px, 2py, 2pz)$	6	8
3	3	3*s*	1	3*s*	2	
		3*p*	3	$3p(3px, 3py, 3pz)$	6	
		3*d*	5	$3d(3dxy, 3dxz, 3dyz, 3dx^2{-}y^2, 3dz^2)$	10	18
4	4	4*s*	1	4*s*	2	
		4*p*	3	$4p(4px, 4py, 4pz)$	6	
		4*d*	5	$4d(4dxy, 4dxz, 4dyz, 4dx^2{-}y^2, 4dz^2)$	10	
		4*f*	7	$4\boldsymbol{f}(4fxyz, 4fx^3, 4fy^3, 4fz^3, 4fz^2{-}y^2, 4fx^2{-}z^2, 4fx^2{-}y^2)$	14	32

3.3 The Shell Model and Chemical Properties

Learning Objective 3 Determine the number of valence shell electrons and the electronic structure for atoms, and relate this information to the location of elements in the periodic table.

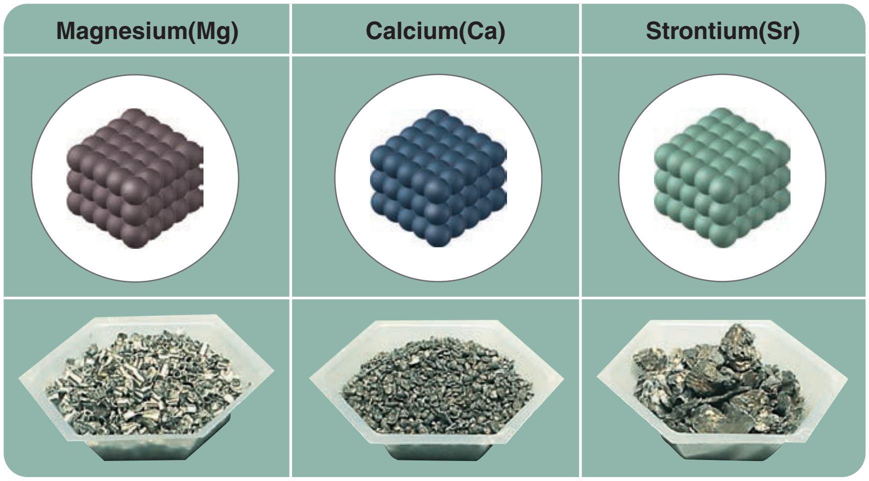
The arrangement of electrons into orbitals, subshells, and shells provides an explanation for the similarities in chemical properties of various elements. **Table 3.2** gives the number of electrons in each shell for the first 20 elements of the periodic table.

TABLE 3.2 Electron Occupancy of Shells

				Electrons in Shell Number			
Element	**Belongs to Group**	**Symbol**	**Atomic Number**	**1**	**2**	**3**	**4**
Hydrogen	IA(1)	H	1	1			
Helium	Noble gas(18)	He	2	2			
Lithium	IA(1)	Li	3	2	1		
Beryllium	IIA(2)	Be	4	2	2		
Boron	IIIA(13)	B	5	2	3		
Carbon	IVA(14)	C	6	2	4		
Nitrogen	VA(15)	N	7	2	5		
Oxygen	VIA(16)	O	8	2	6		
Fluorine	VIIA(17)	F	9	2	7		
Neon	Noble gas(18)	Ne	10	2	8		
Sodium	IA(1)	Na	11	2	8	1	
Magnesium	IIA(2)	Mg	12	2	8	2	
Aluminum	IIIA(13)	Al	13	2	8	3	
Silicon	IVA(14)	Si	14	2	8	4	
Phosphorus	VA(15)	P	15	2	8	5	
Sulfur	VIA(16)	S	16	2	8	6	
Chlorine	VIIA(17)	Cl	17	2	8	7	
Argon	Noble gas(18)	Ar	18	2	8	8	
Potassium	IA(1)	K	19	2	8	8	1
Calcium	IIA(2)	Ca	20	2	8	8	2

In **Table 3.2**, notice that the third shell stops filling when 8 electrons are present, even though the shell can hold a maximum of 18 electrons. The reasons for this are discussed in **Section 3.4**. Also, note that all the elements in a specific group of the periodic table have the same number of electrons in the outermost occupied shell. This outermost occupied shell (the one of highest energy) is called the **valence shell**. Similarities in elemental chemical properties result from identical numbers of electrons in the valence shells of the atoms (see **Figure 3.6**).

valence shell The outermost (highest-energy) shell of an element that contains electrons.



© Spencer L. Seager

FIGURE 3.6 Left to right: Magnesium, calcium, and strontium, members of group IIA(2) of the periodic table, have similar chemical properties and appearances.

Example 3.4 Number of Electrons in Valence Shells for Atoms

Referring to **Table 3.2**, indicate the number of electrons in the valence shell of elements in groups IA(1), IIA(2), IIIA(13), and IVA(14).

Solution

According to **Table 3.2**, the elements in group IA(1) are hydrogen, lithium, sodium, and potassium. Each element has one electron in the valence shell. Hydrogen belongs in group IA(1) on the basis of its electronic structure, but its properties differ significantly from other group members.

The group IIA(2) elements are beryllium, magnesium, and calcium. Each has two electrons in the valence shell. The group IIIA(13) elements are boron and aluminum. Both have three electrons in the valence shell. The group IVA(14) elements are carbon and silicon; each has four valence-shell electrons.

✔ **LEARNING CHECK 3.4** Referring to **Table 3.2**, indicate the number of electrons in the valence shell of elements in groups VA(15), VIA(16), and VIIA(17), and the noble gases(18).

Example 3.4 and Learning Check 3.4 emphasize the fact that elements belonging to the same periodic table group have the same number of electrons in the valence shell (helium, the first element in the noble gases, is an exception). Notice also that the number of electrons in the valence shell is identical to the Roman numeral that designates the group number. Elements of group IIIA(13), for example, have three electrons in the valence shell. It is also apparent that the n value for the valence shell increases by 1 with each heavier member of a group, that is, $n = 2$ for Li, $n = 3$ for Na, and $n = 4$ for K.

Example 3.5 Valence Shell Relationships for Atoms

The barium (Ba) compound, barium sulfate, is used as a contrast agent that allows the digestive tract to be seen more clearly during a radiologic examination.

Using the periodic table and Example 3.4 and Learning Check 3.4, determine the n value for the valence shell and the number of electrons in the valence shell for the following elements:

a. Ba b. Br c. element number 50
d. The third element of group VIA(16)

Solution

a. Ba is the fifth element of group IIA(2), and because $n = 4$ for Ca (the third element of the group), $n = 6$ for the fifth element. The number of valence-shell electrons is two, the same as the group number.
b. In a similar way, Br, the third element of group VIIA(17), has $n = 4$ and seven valence-shell electrons.
c. Element number 50 is tin (Sn), which is the fourth element of group IVA(14). Therefore, $n = 5$ and the number of valence-shell electrons is four.
d. The third element of group VIA(16) is selenium (Se), for which $n = 4$ and the number of valence-shell electrons is six.

✔ **LEARNING CHECK 3.5** How many electrons are present in the following?

a. The valence shell of Sr
b. The valence shell of the third element in group IVA(14)
c. The valence shell of the fifteenth element in period 4

3.4 Electronic Configurations

Learning Objective 4 Determine the following for elements: the electronic configuration of atoms, the number of unpaired electrons in atoms, and the identity of atoms based on provided electronic configurations.

electronic configurations The detailed arrangement of electrons indicated by a specific notation, $1s^2 2s^2 2p^4$, etc.

Hund's rule A statement of the behavior of electrons when they occupy orbitals: Electrons will not pair with other electron in an orbital if an empty orbital of the same energy is available for occupancy.

Pauli exclusion principle A statement of the behavior of electrons when they occupy orbitals: Only electrons spinning in opposite directions can simultaneously occupy the same orbital.

According to **Section 3.3**, similarities in chemical properties between elements are related to the number of electrons that occupy the valence shells of their atoms. We will now look at the electronic arrangements of atoms in more detail. These detailed arrangements, called **electronic configurations**, indicate the number of electrons that occupy each subshell and orbital of an atom.

Imagine that electrons are added one by one to the orbitals that belong to subshells and shells associated with a nucleus. The first electron will go to the lowest energy state as possible, which is represented by the 1*s* orbital of the 1*s* subshell of the first shell. The second electron will join the first and completely fill the 1*s* orbital, the 1*s* subshell, and the first shell (remember, an orbital is filled when it contains two electrons). The third electron will have to occupy the lowest-energy subshell (2*s*) of the second shell. The fourth electron will also occupy (and fill) the 2*s* subshell. The fifth electron must seek out the next–highest-energy subshell, which is the 2*p*. The 2*p* subshell contains three 2*p* orbitals, so the sixth electron can either join the fifth in one of the 2*p* orbitals or go into another empty 2*p* orbital. It will go into an empty orbital in compliance with **Hund's rule**, which states that: Electrons will not pair with other electron in an orbital, if an empty orbital of the same energy is available.

It has been found that electrons behave as if they spin on an axis, and only electrons spinning in opposite directions (indicated by ↑ and ↓) can occupy the same orbital. This principle, known as the **Pauli exclusion principle** in honor of Wolfgang Pauli (see **Figure 3.7**), explains why orbitals can contain a maximum of two electrons. Hund's rule and the Pauli exclusion principle can be combined: Electrons will pair with other electron in an orbital only if there is no empty orbital of the same energy available and if there is one electron with opposite spin already in the orbital.

The seventh added electron will occupy the last empty 2*p* orbital, and the eighth, ninth, and tenth electrons will pair up with electrons already in the 2*p* orbitals. The tenth electron fills the 2*p* subshell, thus completing the second shell. This filling order is illustrated in **Figure 3.8**.

Keystone Press/Alamy Stock Photo

FIGURE 3.7 Wolfgang Pauli was an Austrian theoretical physicist.

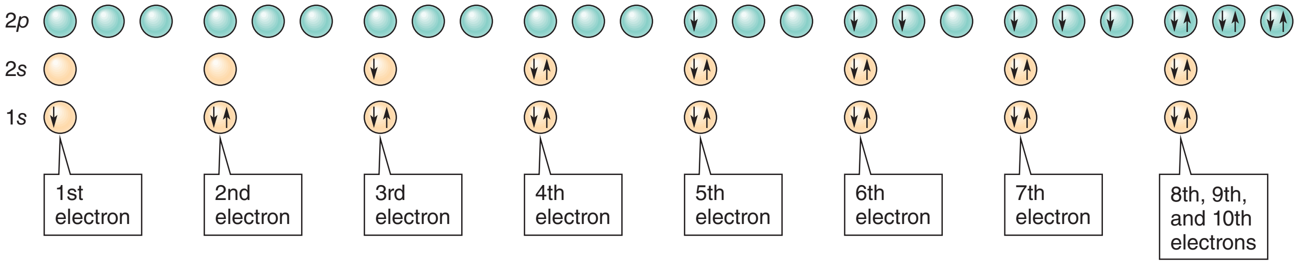


FIGURE 3.8 The filling order for the first 10 electrons.

The eleventh electron, with no empty orbital available that has the same energy as a 2*p* and no partially filled orbitals, will occupy the empty lowest-energy subshell of the third shell. The filling order for electrons beyond the tenth follows the pattern given in **Figure 3.9**, where shells are indicated by large rectangles, subshells by colored rectangles, and orbitals by circles. The filling order is obtained by following the arrows.

As shown in **Figure 3.9**, some low-energy subshells of a specific shell have energies lower than the upper subshell of a preceding shell. For example, the 4*s* subshell has a lower energy than, and fills before, the 3*d* subshell. **Figure 3.9** indicates that the third shell will not accept more than 8 electrons until the 4*s* subshell is complete. Thus, electrons 21 through 30 go into the 3*d* subshell and complete the filling of the third shell.

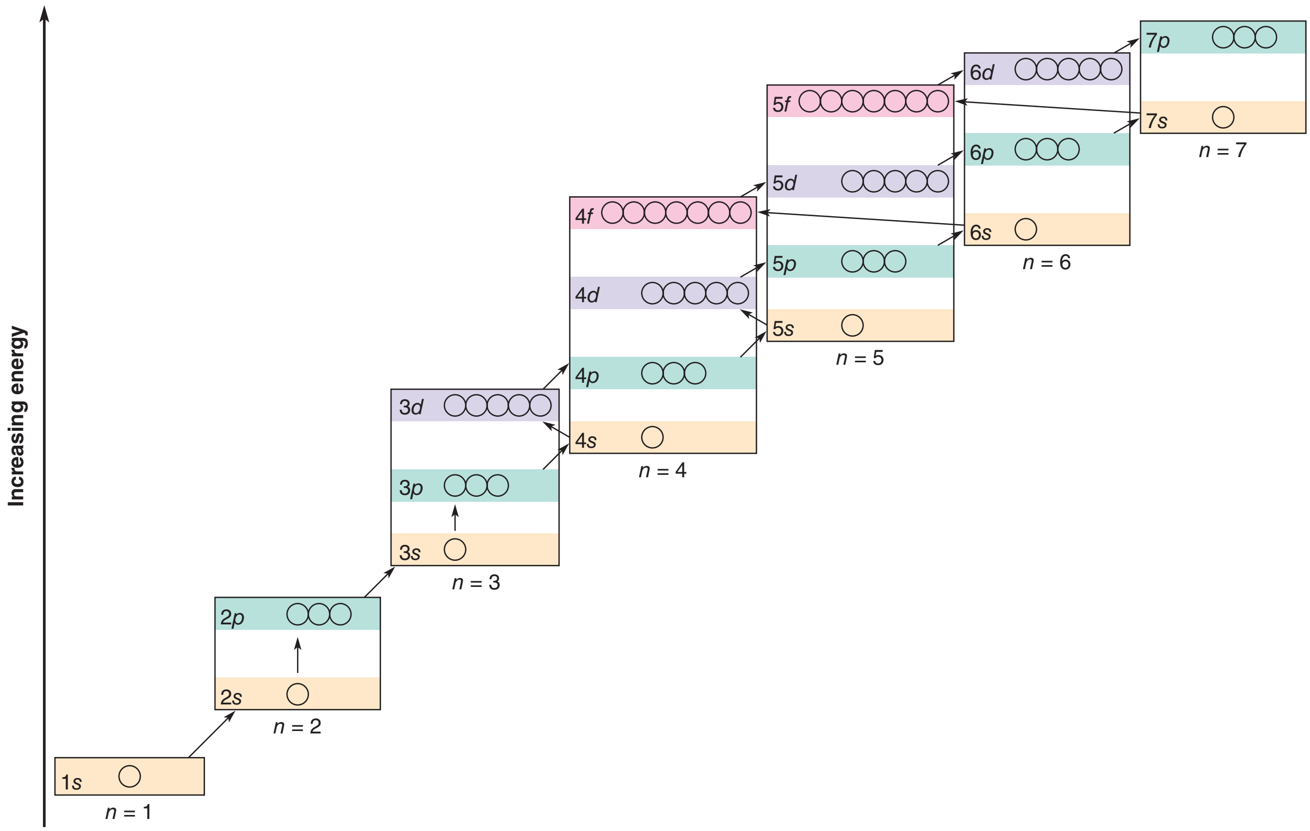


FIGURE 3.9 The relative energies and electron-filling order for shells and subshells.

It is often convenient to represent the electronic configuration of an atom in a concise way. This is done by writing the subshells in the correct filling order and then indicating the number of electrons in each subshell by a superscript.

Example 3.6 Electronic Configurations and Unpaired Electrons

Write the electronic configurations for the following, and indicate the number of unpaired electrons in each case:

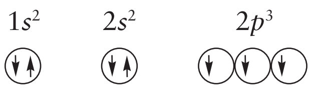
a. An atom that contains 7 electrons
b. An atom that contains 17 electrons
c. An atom of element number 22
d. An atom of arsenic (As). Arsenic is known for its toxicity and may play a role in the development of a number of serious conditions.

Solution

The correct filling order of subshells from **Figure 3.9** is

$$1s, 2s, 2p, 3s, 3p, 4s, 3d, 4p, 5s, 4d, 5p, 6s, 4f, 5d, 6p, 7s, 5f, 6d, 7p$$

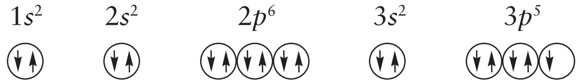
a. Even though *s* subshells can hold 2 electrons, *p* subshells 6, *d* subshells 10, and *f* subshells 14, only enough subshells to hold 7 electrons will be used. Therefore, the configuration is written as shown below, starting on the left, with circles representing orbitals and arrows representing electrons. It is apparent that no subshells beyond 2*p* are needed because that subshell contains only 3 electrons. Note that both the 1*s* and 2*s* subshells are full; the 2*p* subshell is half-full, with one electron in each of the three orbitals (Hund's rule; see **Figure 3.10**). These three electrons are unpaired.



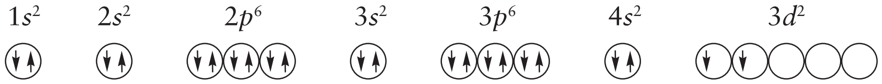
Heinz-Jürgen Göttert/picture alliance/Getty Images

FIGURE 3.10 Friedrich Hund, a German physicist, proposed in 1925 that electrons will not join others in an orbital if an empty orbital of the same energy is available.

b. Similarly, the configuration for 17 electrons is shown below. Here the 1*s*, 2*s*, 2*p*, and 3*s* subshells are full, as are the first and second shells. The 3*p* subshell is not full and can accept 1 more electron. One electron in the 3*p* subshell is unpaired.



c. An atom of element number 22 contains 22 protons in the nucleus and must therefore contain 22 electrons. The electronic configuration is



Note here that only two of the 3d orbitals of the 3d subshell are occupied, and each of these orbitals contains a single electron. Thus, there are two unpaired electrons.

d. Arsenic (As) is element number 33 and therefore contains 33 electrons. The electronic configuration is

$$1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^3$$

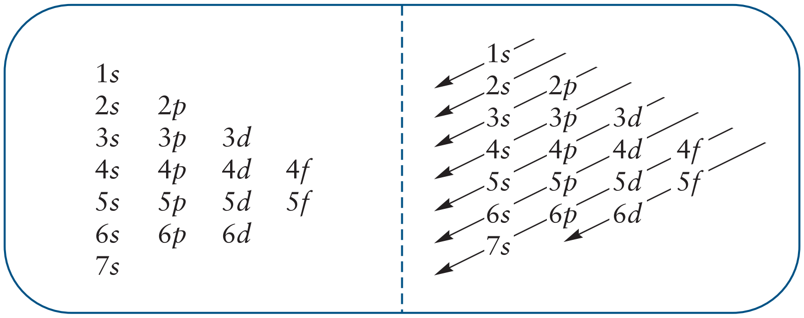
This time, the circles and arrows have not been used to indicate orbitals and electrons. You should satisfy yourself that the following facts are clear: The first, second, and third shells are full. The fourth shell is partially full, with the 4*s* subshell being full and the 4*p* subshell being half-filled. The 4*p* subshell contains three unpaired electrons.

✔ LEARNING CHECK 3.6 Write the electronic configurations for the following, and indicate the number of unpaired electrons in each case:

a. Element number 9
b. Mg
c. The element found in group VIA(16) and period 3
d. An atom that contains 23 protons

Although **Figure 3.9** gives the details of subshell-filling order, a more concise diagram is available and easy to remember. It is shown in **Figure 3.11**, where the subshells are first arranged as shown on the left and then diagonal arrows are drawn as shown on the right. To get the correct subshell-filling order, follow the arrows from top to bottom, going from the head of one arrow to the tail of the next.

FIGURE 3.11 An aid to remembering subshell-filling order.



The electronic configurations described to this point provide details of the shells, subshells, and orbitals involved but are somewhat cumbersome. In some applications, these details are not needed, and simplified representations are used that emphasize the electrons in the valence shell.

STUDY TOOLS 3.1

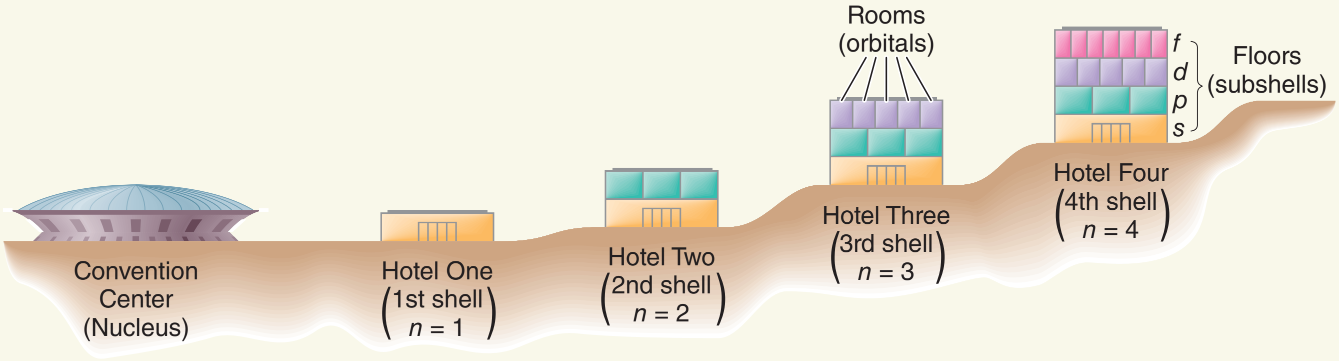
The Convention Hotels Analogy

A new concept is often made easier to understand by relating it to something familiar. You are probably familiar with the way rooms, floors, and hotels located near a convention center will fill with convention delegates. Imagine that the hotels are located on a street that runs uphill from the convention center, as shown. Further imagine that none of the hotels have elevators, so the only way to get to upper floors is to climb the stairs.

In this analogy, the convention center is equivalent to the nucleus of an atom, and each hotel represents a shell, each floor represents a subshell, and each room represents an orbital. If you were a delegate who wanted to describe to a friend where you were staying, you would indicate the hotel (shell), floor (subshell), and room (orbital) assigned to you. Electronic configurations such as $1s^22s^22p^1$ give similar information for each electron: The numbers preceding each letter indicate the shells, the letters indicate the subshells, and the superscripts coupled with Hund's rule indicate which orbitals are occupied.

Three more assumptions allow us to extend the analogy: (1) not more than two delegates can be assigned to a room, (2) delegates prefer not to have roommates if an empty room on the same floor is available, and (3) all delegates want to use as little energy as possible when they walk from the convention center to their rooms (remember, there are no elevators).

With these assumptions in mind, it is obvious that the first delegate to check in will choose to stay in the single room of the *s* floor of Hotel One (a small but very exclusive hotel). The second delegate will also choose this same floor and room of Hotel One and will fill the hotel to capacity. The third delegate will have to go to Hotel Two and will choose the one room on the *s* floor. The fourth delegate will also choose the one room remaining on the *s* floor, and fill that floor. The fifth delegate will choose a room on the *p* floor of Hotel Two because the *s* floor is full. The sixth delegate will also choose a room on the *p* floor of Hotel Two but will choose one that is not occupied. The seventh delegate will also choose an empty room on the *p* floor of Hotel Two. Delegates eight, nine, and ten can either pair up with the delegates already in the rooms of the *p* floor of Hotel Two or go uphill to Hotel Three. They choose to save energy by not walking up the stairs and staying in rooms with roommates already on the *p* floor of Hotel Two. Additional arriving delegates will occupy the floors of Hotels Three and Four in the order dictated by these same energy and pairing considerations. Thus, we see that the delegates in their rooms are analogous to the electrons in their orbitals.


Rooms (orbitals)
f
d
p
s
Floors (subshells)
Convention Center (Nucleus)
Hotel One (1st shell n = 1)
Hotel Two (2nd shell n = 2)
Hotel Three (3rd shell n = 3)
Hotel Four (4th shell n = 4)

We see from **Table 3.2** that the noble gases neon and argon both have electronic configurations that end with a completely filled *p* subshell. This is true for all noble gases except helium, which ends with a filled 1*s* subshell. In Chapter 4, we will see that these **noble gas configurations** are important in understanding the bonding that occurs between atoms.

Noble gas configurations can be used to write abbreviated electronic configurations. Instead of writing the configurations in their entirety, the symbols for the noble gases are used in brackets to represent the electrons found in their configurations.

noble gas configuration An electronic configuration in which the last eight electrons occupy and fill the *s* and *p* subshells of the highest-occupied shell.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Electrons that are present in addition to those of the noble gases are written according to the following symbol. For example, the electronic configuration for sodium can be represented as $1s^22s^22p^63s^1$ or $[Ne]3s^1$.

Example 3.7 Abbreviated Electronic Configurations

Write abbreviated electronic configurations for the following:

a. An atom that contains 7 electrons
b. An atom that contains 17 electrons
c. An atom of element number 22
d. An atom of arsenic (As)

Solution

All these configurations were written in conventional form in Example 3.6.

a. From Example 3.6, the configuration is $1s^22s^22p^3$. We see that the two electrons in the $1s$ subshell represent the noble gas configuration of helium (He), so we can write the configuration as $[He]2s^22p^3$.
b. From Example 3.6, the configuration is $1s^22s^22p^63s^23p^5$. We see that the $1s^22s^22p^6$ portion is the configuration of neon (Ne), so we can write the configuration as $[Ne]3s^23p^5$.
c. From Example 3.6, the configuration is $1s^22s^22p^63s^23p^64s^23d^2$. We see that the first 18 electrons represented by $1s^22s^22p^63s^23p^6$ correspond to the electrons of argon (Ar). Thus, we can write the configuration as $[Ar]4s^23d^2$.
d. From Example 3.6, the configuration of arsenic is $1s^22s^22p^63s^23p^64s^23d^{10}4p^3$. Once again, the first 18 electrons can be represented by the symbol for argon. The configuration is $[Ar]4s^23d^{10}4p^3$.

✔ **LEARNING CHECK 3.7** Write abbreviated electronic configurations for the following. These are the same elements used in Learning Check 3.6.

a. An atom of element number 9
b. An atom of magnesium (Mg)
c. An atom of the element found in group VIA(16) and period 3
d. An atom that contains 23 protons

3.5 Another Look at the Periodic Table

Learning Objective 5 Determine the shell and subshell locations of the distinguishing electrons in elements, and based on their location in the periodic table, classify elements into the categories given in **Figures 3.13** and **3.16**.

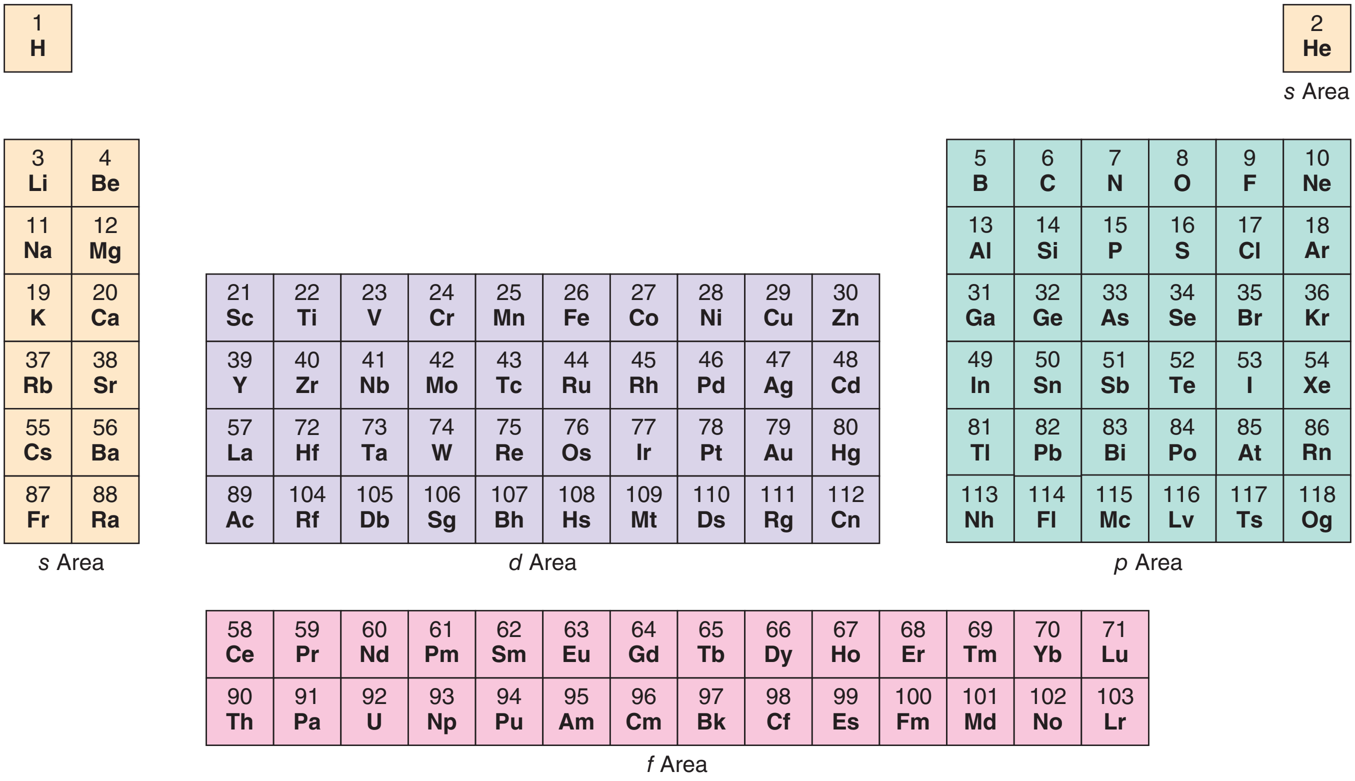
Now that you know more about electronic configurations, you can better understand the periodic law and table. First, consider the electronic configurations of the elements belonging to the same group of the periodic table. Group IA(1), for example, contains Li, Na, K, Rb, Cs, and Fr, with electronic configurations for the first four elements as shown below:

Element Symbol	Conventional Form	Abbreviated Form
Li	$1s^22s^1$	$[He]2s^1$
Na	$1s^22s^22p^63s^1$	$[Ne]3s^1$
K	$1s^22s^22p^63s^23p^64s^1$	$[Ar]4s^1$
Rb	$1s^22s^22p^63s^23p^64s^23d^{10}4p^65s^1$	$[Kr]5s^1$

Notice that each of these elements has a single electron in the valence shell. Further, each of these valence-shell electrons is located in *s* subshell. Elements belonging to other groups also have valence-shell electronic configurations that are similar for all members of the group, and all members have similar chemical properties. It has been determined that the similar chemical properties of elements in the same group result from similar valence-shell electronic configurations.

The periodic table becomes more useful when we interpret it in terms of the electronic configurations of the elements in various areas. One relationship is shown in **Figure 3.12**, where the periodic table is divided into four areas on the basis of the type of subshell occupied by the highest-energy electron in the atom. This last electron added to an atom is called the **distinguishing electron**. Note that the *s* area is 2 columns (elements) wide, the *p* area is 6 columns wide, the *d* area is 10 columns wide, and the *f* area is 14 columns wide—exactly the number of electrons required to fill the *s*, *p*, *d*, and *f* subshells, respectively.

distinguishing electron The last and highest-energy electron found in an element.



1 **H**																	2 **He**
3 **Li**	4 **Be**											5 **B**	6 **C**	7 **N**	8 **O**	9 **F**	10 **Ne**
11 **Na**	12 **Mg**											13 **Al**	14 **Si**	15 **P**	16 **S**	17 **Cl**	18 **Ar**
19 **K**	20 **Ca**	21 **Sc**	22 **Ti**	23 **V**	24 **Cr**	25 **Mn**	26 **Fe**	27 **Co**	28 **Ni**	29 **Cu**	30 **Zn**	31 **Ga**	32 **Ge**	33 **As**	34 **Se**	35 **Br**	36 **Kr**
37 **Rb**	38 **Sr**	39 **Y**	40 **Zr**	41 **Nb**	42 **Mo**	43 **Tc**	44 **Ru**	45 **Rh**	46 **Pd**	47 **Ag**	48 **Cd**	49 **In**	50 **Sn**	51 **Sb**	52 **Te**	53 **I**	54 **Xe**
55 **Cs**	56 **Ba**	57 **La**	72 **Hf**	73 **Ta**	74 **W**	75 **Re**	76 **Os**	77 **Ir**	78 **Pt**	79 **Au**	80 **Hg**	81 **Tl**	82 **Pb**	83 **Bi**	84 **Po**	85 **At**	86 **Rn**
87 **Fr**	88 **Ra**	89 **Ac**	104 **Rf**	105 **Db**	106 **Sg**	107 **Bh**	108 **Hs**	109 **Mt**	110 **Ds**	111 **Rg**	112 **Cn**	113 **Nh**	114 **Fl**	115 **Mc**	116 **Lv**	117 **Ts**	118 **Og**

58 **Ce**	59 **Pr**	60 **Nd**	61 **Pm**	62 **Sm**	63 **Eu**	64 **Gd**	65 **Tb**	66 **Dy**	67 **Ho**	68 **Er**	69 **Tm**	70 **Yb**	71 **Lu**
90 **Th**	91 **Pa**	92 **U**	93 **Np**	94 **Pu**	95 **Am**	96 **Cm**	97 **Bk**	98 **Cf**	99 **Es**	100 **Fm**	101 **Md**	102 **No**	103 **Lr**

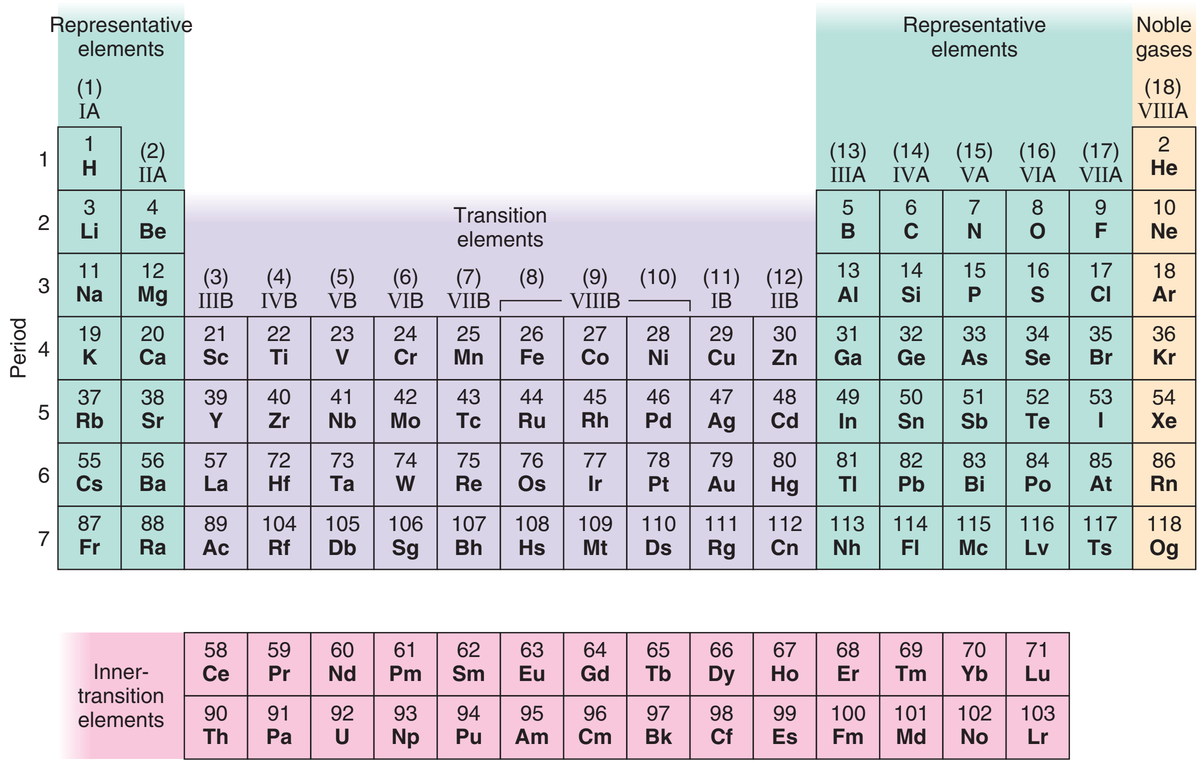
FIGURE 3.12 The periodic table divided by distinguishing electrons of the elements.

Electronic configurations are also used to classify elements of the periodic table, as shown in **Figure 3.13**.

The *noble gases* make up the group of elements found on the extreme right of the periodic table. They are all gases at room temperature and are unreactive with most other substances (hence, the group name). With the exception of helium, the first member of the group, noble gases are characterized by filled *s* and *p* subshells of the highest occupied shell.

Representative elements are those found in the *s* and *p* areas of the periodic table, not including the noble gases. The distinguishing electrons of representative elements partially or completely fill an *s* subshell—groups IA(1) and IIA(2)—or partially fill a *p* subshell—groups IIIA(13), IVA(14), VA(15), VIA(16), and VIIA(17). Most of the common elements are representative elements.

representative element An element in which the distinguishing electron is found in an *s* or a *p* subshell.



Period	Representative elements (1) IA	(2) IIA	Transition elements (3) IIIB	(4) IVB	(5) VB	(6) VIB	(7) VIIB	(8)	(9) VIIIB	(10)	(11) IB	(12) IIB	Representative elements (13) IIIA	(14) IVA	(15) VA	(16) VIA	(17) VIIA	Noble gases (18) VIIIA
1	1 **H**																	2 **He**
2	3 **Li**	4 **Be**											5 **B**	6 **C**	7 **N**	8 **O**	9 **F**	10 **Ne**
3	11 **Na**	12 **Mg**											13 **Al**	14 **Si**	15 **P**	16 **S**	17 **Cl**	18 **Ar**
4	19 **K**	20 **Ca**	21 **Sc**	22 **Ti**	23 **V**	24 **Cr**	25 **Mn**	26 **Fe**	27 **Co**	28 **Ni**	29 **Cu**	30 **Zn**	31 **Ga**	32 **Ge**	33 **As**	34 **Se**	35 **Br**	36 **Kr**
5	37 **Rb**	38 **Sr**	39 **Y**	40 **Zr**	41 **Nb**	42 **Mo**	43 **Tc**	44 **Ru**	45 **Rh**	46 **Pd**	47 **Ag**	48 **Cd**	49 **In**	50 **Sn**	51 **Sb**	52 **Te**	53 **I**	54 **Xe**
6	55 **Cs**	56 **Ba**	57 **La**	72 **Hf**	73 **Ta**	74 **W**	75 **Re**	76 **Os**	77 **Ir**	78 **Pt**	79 **Au**	80 **Hg**	81 **Tl**	82 **Pb**	83 **Bi**	84 **Po**	85 **At**	86 **Rn**
7	87 **Fr**	88 **Ra**	89 **Ac**	104 **Rf**	105 **Db**	106 **Sg**	107 **Bh**	108 **Hs**	109 **Mt**	110 **Ds**	111 **Rg**	112 **Cn**	113 **Nh**	114 **Fl**	115 **Mc**	116 **Lv**	117 **Ts**	118 **Og**

Inner-transition elements														
58 **Ce**	59 **Pr**	60 **Nd**	61 **Pm**	62 **Sm**	63 **Eu**	64 **Gd**	65 **Tb**	66 **Dy**	67 **Ho**	68 **Er**	69 **Tm**	70 **Yb**	71 **Lu**	
90 **Th**	91 **Pa**	92 **U**	93 **Np**	94 **Pu**	95 **Am**	96 **Cm**	97 **Bk**	98 **Cf**	99 **Es**	100 **Fm**	101 **Md**	102 **No**	103 **Lr**	

FIGURE 3.13 Elemental classification on the basis of electronic configurations.

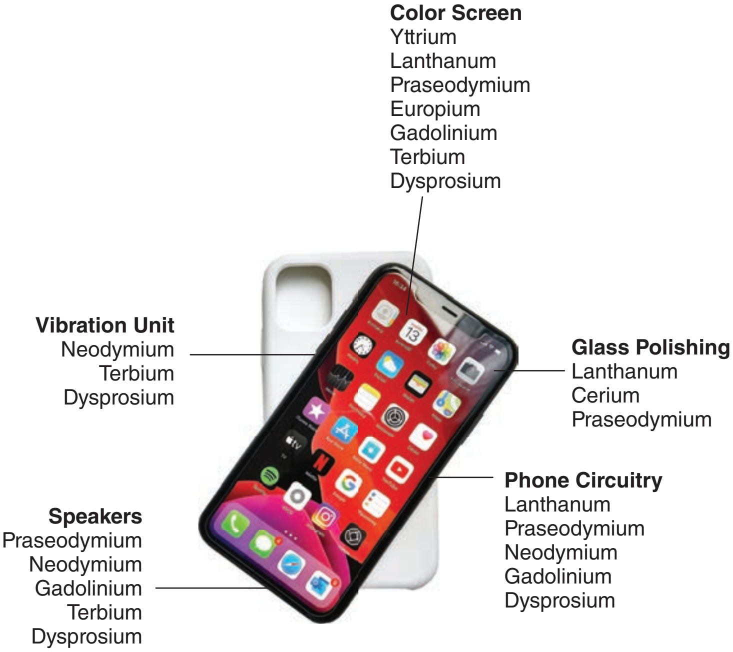
The *d* area of the periodic table contains the **transition elements** (**Figure 3.13**), in which the distinguishing electron is found in a *d* subshell. Some transition elements are used for everyday applications (**Figure 3.14**). **Inner-transition elements** (see **Figure 3.15**) are those in the *f* area of the periodic table, and the distinguishing electron is found in an *f* subshell.

transition element An element in which the distinguishing electron is found in a *d* subshell.

inner-transition element An element in which the distinguishing electron is found in *f* subshell.

iStock.com/Cveltri

FIGURE 3.14 Transition elements, such as gold, silver, copper, nickel, platinum, and zinc, are often used in coins and medals. List some chemical and physical properties that would be desirable in metals used for such purposes.


Color Screen
Yttrium
Lanthanum
Praseodymium
Europium
Gadolinium
Terbium
Dysprosium
Vibration Unit
Neodymium
Terbium
Dysprosium
Glass Polishing
Lanthanum
Cerium
Praseodymium
Speakers
Praseodymium
Neodymium
Gadolinium
Terbium
Dysprosium
Phone Circuitry
Lanthanum
Praseodymium
Neodymium
Gadolinium
Dysprosium

David Švihovec/Unsplash.com

FIGURE 3.15 Transition and inner-transition elements play important roles in your smart phone.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS 3.2

Zinc for Colds?

The common cold is the number one medical reason for missed work and school absenteeism. While there is no known cure, some evidence from studies done during the past 30 years indicates that certain zinc-containing chemical compounds, when taken internally, have the ability to shorten the duration and reduce the severity of cold symptoms.

In a 100-patient study done at the Cleveland Clinic, patients were given lozenges within 24 hours of first showing symptoms of the common cold. Half the patients received lozenges that contained the compound zinc gluconate. The other half received placebo lozenges that contained no zinc compounds. During their waking hours, all patients dissolved a lozenge in their mouth every 2 hours. The results of this study showed that cold symptoms lasted an average of 4.4 days in patients who received the zinc gluconate, compared to an average duration of 7.6 days in patients who received the non-zinc placebos.

Researchers continue to study this topic till today. As a result of these studies, there is fair evidence that the use of zinc gluconate lozenges does marginally reduce the duration of the common cold compared to a placebo. However, the design of these studies has been called into question, so the conclusions are still considered to be somewhat tentative.

RobertChlopas/Shutterstock.com

Zinc-containing lozenges may marginally reduce the duration of the common cold.

Example 3.8 Distinguishing Electrons and Element Classifications

Iron (Fe) is a mineral vital to the transport of oxygen within the bloodstream.

Use the periodic table and **Figures 3.12** and **3.13** to determine the following for Ca, Fe, S, and Kr:

a. The type of distinguishing electron
b. The classification based on **Figure 3.13**

Solution

a. On the basis of the location of each element in **Figure 3.12**, the distinguishing electrons are of the following types:

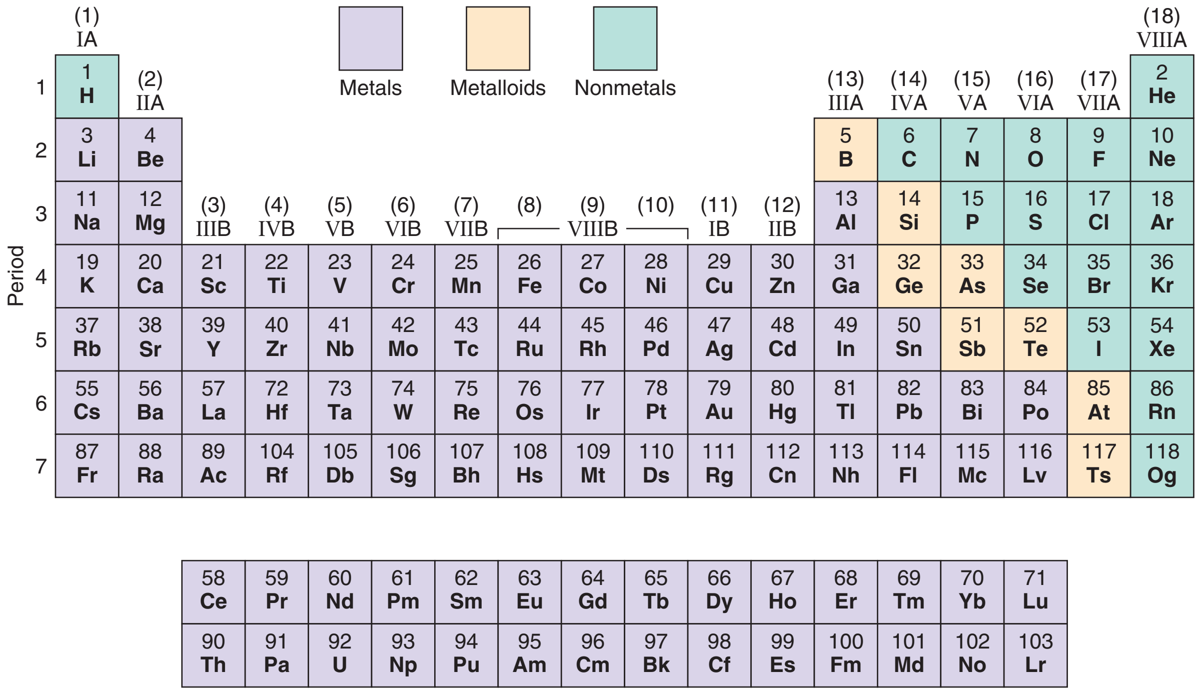
Ca: *s* Fe: *d* S: *p* Kr: *p*

b. The classifications based on **Figure 3.13** are: Ca, representative element; Fe, transition element; S, representative element; Kr, noble gas.

✔ **LEARNING CHECK 3.8** Determine the following for element numbers 38, 47, 50, and 86:

a. The type of distinguishing electron
b. The classification according to **Figure 1.13**

The elements can also be classified into the categories of metals, nonmetals, and metalloids. This approach, used in **Figure 3.16**, shows that most elements are classified as metals. It is also apparent from **Figure 3.13** that most nonmetals and all metalloids are representative elements.


Metals
Metalloids
Nonmetals

Period	(1) IA	(2) IIA	(3) IIIB	(4) IVB	(5) VB	(6) VIB	(7) VIIB	(8)	(9) VIIIB	(10)	(11) IB	(12) IIB	(13) IIIA	(14) IVA	(15) VA	(16) VIA	(17) VIIA	(18) VIIIA
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

FIGURE 3.16 Locations of metals, nonmetals, and metalloids in the periodic table of the elements.

metals Elements found in the left two-thirds of the periodic table. Most have the following properties: high thermal and electrical conductivities, high malleability and ductility, and a luster.

Most **metals** have the following properties. (Are these properties physical or chemical?)

High thermal conductivity—they transmit heat readily.
High electrical conductivity—they transmit electricity readily.
Ductility—they can be drawn into wires.
Malleability—they can be hammered into thin sheets.
Luster—they have a characteristic "metallic" appearance.

nonmetals Elements found in the right one-third of the periodic table. They often occur as brittle, powdery solids or gases and have properties generally opposite to those of metals.

metalloids Elements that form a narrow diagonal band in the periodic table between metals and nonmetals. They have properties somewhat between those of metals and nonmetals.

Nonmetals, the elements found in the right one-third of the periodic table, generally have chemical and physical properties opposite to those of metals. Under normal conditions, they often occur as brittle, powdery solids or as gases.

Metalloids, such as boron (B) and silicon (Si), are the elements that form a diagonal separate zone between metals and nonmetals in the periodic table. Metalloids have properties somewhat between those of metals and nonmetals, and they often exhibit some of the characteristic properties of each type.

✔ **LEARNING CHECK 3.9** Classify each of the following elements as metal, nonmetal, or metalloid:

a. Xe b. As c. Hg d. Ba e. Th

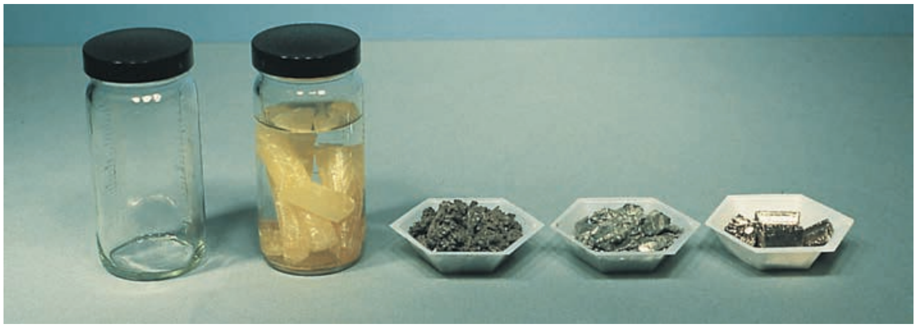
3.6 Property Trends within the Periodic Table

Learning Objective 6 Recognize property trends of elements within the periodic table, and use the trends to predict selected properties of the elements.

In **Figure 3.16**, the elements are classified into the categories of metal, metalloid, or nonmetal according to their positions in the table and properties such as thermal conductivity and metallic luster. It is generally true that within a period of the periodic table, the elements become less metallic as we move from left to right. Within a group, the metallic character increases from top to bottom.

Consider group VA(15) as an example. We see that the elements of the group consist of the two nonmetals, nitrogen (N) and phosphorus (P), skip two metalloids, arsenic (As) and antimony (Sb), and the metal bismuth (Bi). We see the trend toward more metallic character from top to bottom that was mentioned above. According to what has been discussed concerning the periodic law and periodic table, these elements should have some similarities in chemical properties, because they belong to the same group of the periodic table. Studies of their chemical properties show that they are similar but not identical. Instead, they follow trends according to the location of the elements within the group.

Certain physical properties also follow such trends, and some of these are easily observed, as shown in **Figure 3.17**. At room temperature and ordinary atmospheric pressure, nitrogen is a colorless gas, phosphorus is a white nonmetallic solid, arsenic is a brittle gray solid with a slight metallic luster, antimony is a brittle silver-white solid with a metallic luster, and bismuth is a lustrous silver-white metal.

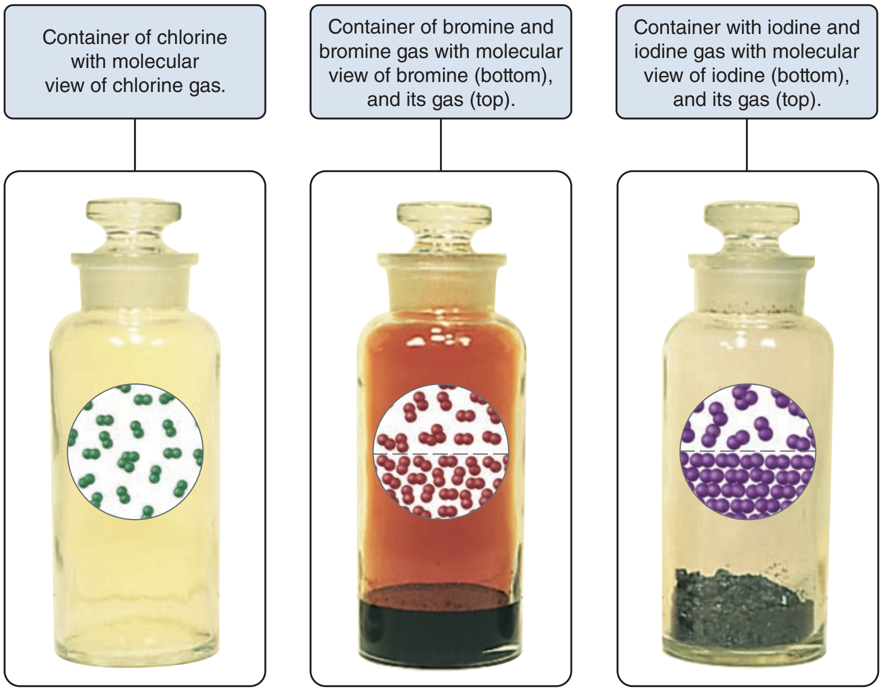


© Spencer L. Seager

FIGURE 3.17 The elements of group VA(15) of the periodic table. Phosphorus must be stored under water because it will ignite when exposed to the oxygen in air. It has a slight color because of reactions with air.

We see that these physical properties are certainly not identical, but we do see that they change in a somewhat regular way (they follow a trend) as we move from element to element down the group. Nitrogen is a gas, but the others are solids. Nitrogen is colorless, phosphorus is white, and the rest three elements of the group shows more metallic characteristics. Also, as mentioned previously, we note a change from nonmetal to metalloid to metal as we move down the group.

The trends in these properties occur in a regular way that would allow us to predict some of them for one element if they were known for the other elements in the group. For example, if the properties of bismuth were unknown, we would have predicted that it would have a silvery white color and a metallic luster based on the appearance of arsenic and antimony. The three elements from group VIIA(17) shown in **Figure 3.18** also demonstrate some obvious predictable trends in physical properties.


Container of chlorine with molecular view of chlorine gas.
Container of bromine and bromine gas with molecular view of bromine (bottom), and its gas (top).
Container with iodine and iodine gas with molecular view of iodine (bottom), and its gas (top).

© Jeffrey M. Seager

FIGURE 3.18 Chlorine, bromine, and iodine (left to right) all belong to group VIIA(17) of the periodic table. Their atoms all have the same number of electrons in the valence shell and therefore similar chemical properties. However, they do not have similar appearances. At room temperature and under normal atmospheric pressure, chlorine is a pale yellow gas, bromine is a dark red liquid that readily changes into a gas, and iodine is a gray-black solid that changes into a purple gas when heated slightly. Astatine is the next member of the group after iodine. Try to think like Mendeleev and predict its color and whether it will be a liquid, solid, or gas under normal conditions.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Trends in properties occur in elements that form periods across the periodic table as well as among those that form vertical groups. We will discuss two of these properties and their trends for representative elements. Our focus will be on the general trends, recognizing that some elements show deviations from these general behaviors. We will also propose explanations for the trends based on the electronic structure of atoms discussed in the chapter.

The first property we will consider is the size of the atoms of the representative elements. The size of an atom is considered to be the radius of a sphere extending from the center of the nucleus of the atom to the location of the outermost electrons around the nucleus. The behavior of this property across a period and down a group is shown in **Figure 3.19**. We see that the size increases from the top to the bottom of each group, and decreases from left to right across a period.

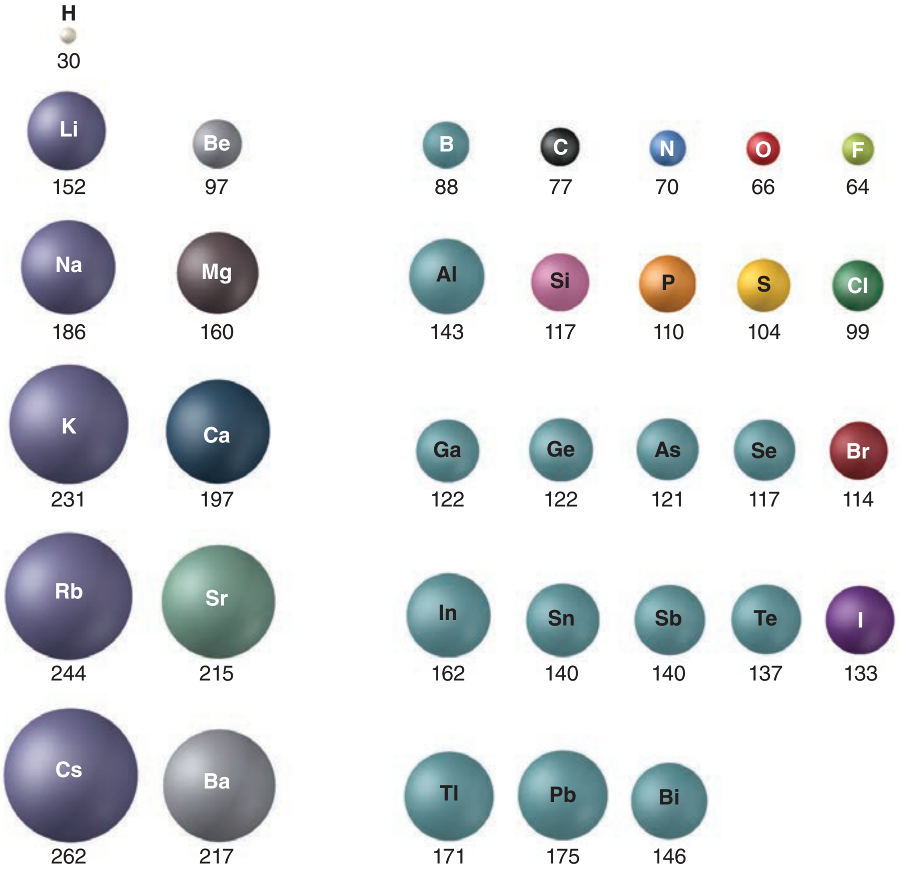


FIGURE 3.19 Scale drawings of the atoms of some representative elements enlarged about 60 million times. The numbers are the atomic radii in picometers (10^{-12} m).

Remember that when we go from element to element down a group, a new electronic shell is being filled. Consider group IA(1). In lithium atoms (Li), the second shell ($n = 2$) is being filled, in sodium atoms (Na), the third shell ($n = 3$) is being filled, and so on for each element in the group until the sixth shell ($n = 6$) begins to fill in cesium atoms (Cs). As n increases, the distance of the electrons from the nucleus in the shell designated by n increases, and the atomic radius as defined above also increases.

The decrease in atomic radius across a period can also be understood in terms of the outermost electrons around the nucleus. Consider period 3, for example. The abbreviated electronic configuration for sodium atoms (Na) is [Ne]$3s^1$, and the outermost electron is in the third shell ($n = 3$). In magnesium atoms (Mg), the electronic structure is [Ne]$3s^2$, and we see that the outermost electron is still in the third shell. In aluminum atoms (Al), the electronic structure is [Ne]$3s^23p^1$, and we see that, once again, the outermost electron lies in the third shell. In fact, the outermost electrons in all the atoms across period 3 are in the third shell.

Because all these electrons are in the same third shell, they should all be the same distance from the nucleus, and the atoms should all be the same size. However, each time another electron is added to the third shell of these elements and another positively charged proton is added to the nucleus. Thus, in sodium atoms there are 11 positive nuclear charges attracting the electrons, but in aluminum atoms there are 13. The effect of the increasing nuclear charge attracting electrons in the same shell is to pull all the electrons of the shell closer to the nucleus and cause the atomic radii to decrease as the nuclear charge increases.

The chemical reactivity of elements is dependent on the behavior of the electrons of the atoms of the elements, especially the valence electrons. One property that is related to the behavior of the electrons of atoms is the ionization energy.

The *ionization energy* of an element is the energy required to remove an outermost electron from an atom of the element in the gaseous state. The removal of one electron from an atom leaves the atom with a net 1+ charge, because the nucleus of the resulting atom contains one more proton than the number of remaining electrons. The resulting charged atom is called an *ion*. We will discuss ions and the ionization process in more detail in **Sections 4.2** and **4.3**. A reaction for the removal of one electron from an atom of sodium is

$$Na(g) \rightarrow Na^+(g) + e^-$$

Because this process represents the removal of the first electron from a neutral sodium atom, the energy necessary to accomplish the process is called the **first ionization energy**. If a second electron were removed, the energy required would be called the second ionization energy, and so on. We will focus on only the first ionization energy for representative elements. **Figure 3.20** contains values for the first ionization energy of a number of representative elements.

first ionization energy The energy required to remove the first outermost electron from a neutral atom.

IA	IIA	IIIA	IVA	VA	VIA	VIIA	VIIIA
H 1311							**He** 2370
Li 521	**Be** 899	**B** 799	**C** 1087	**N** 1404	**O** 1314	**F** 1682	**Ne** 2080
Na 496	**Mg** 737	**Al** 576	**Si** 786	**P** 1052	**S** 1000	**Cl** 1245	**Ar** 1521
K 419	**Ca** 590	**Ga** 576	**Ge** 784	**As** 1013	**Se** 939	**Br** 1135	**Kr** 1351
Rb 402	**Sr** 549	**In** 559	**Sn** 704	**Sb** 834	**Te** 865	**I** 1007	**Xe** 1170
Cs 375	**Ba** 503	**Tl** 590	**Pb** 716	**Bi** 849	**Po** 791	**At** 926	**Rn** 1037

FIGURE 3.20 First ionization energies for selected representative elements. The values are given in kJ/mol. (Source: Data from Bard, A. J.; Parsons, R.; Jordan, J. *Standard Potentials in Aqueous Solution*. New York: Dekker, 1985, pp. 24–27.)

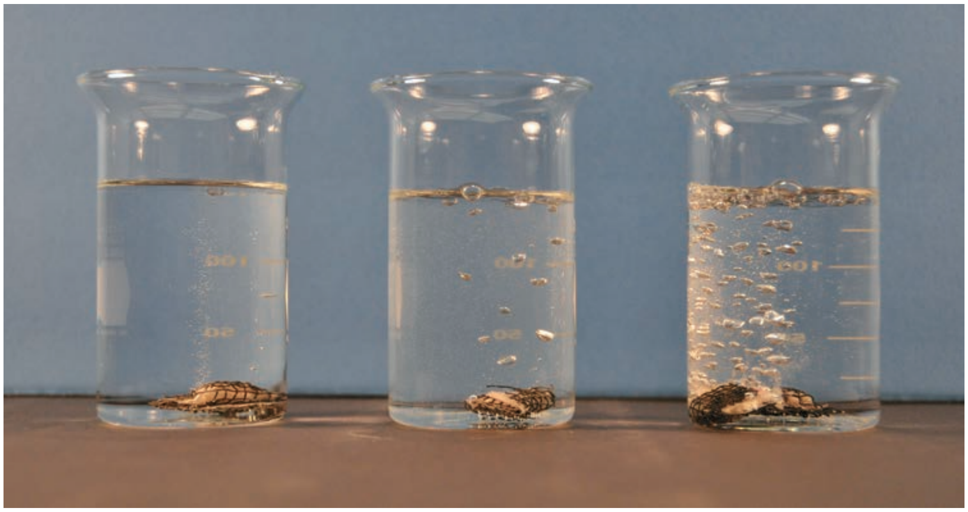
The general trend is seen to be a decrease from top to the bottom of a group, and an increase from left to right across a period. The higher the value of the ionization energy, the more difficult it is to remove an electron from the atoms of an element. Thus, we see that in general, the electrons of metals are more easily removed than are the electrons of nonmetals. Also, the farther down a group a metal is located, the easier it is to remove an electron.

The metals of group IA(1) all react with ethyl alcohol, C_2H_5OH, to produce hydrogen gas, H_2, as follows, where M is a general representation of the metals of the group:

$$2M + 2C_2H_5OH \rightarrow 2C_2H_5OM + H_2(g)$$

In this reaction, electrons are removed from the metal and transferred to the hydrogen. The reaction is shown in progress for the first three members of the group in **Figure 3.21**. The rate (speed) of the reaction is indicated by the amount of hydrogen gas being released.

FIGURE 3.21 The reaction of group IA(1) elements with ethyl alcohol. Left to right: Lithium (Li), sodium (Na), potassium (K). Each metal sample was wrapped in a wire screen to keep it from floating.



© Jeffrey M. Seager

✔ **LEARNING CHECK 3.10** Refer to **Figure 3.21**, and do the following:

a. Arrange the three metals of the group vertically in order of the rate of the reaction with ethyl alcohol. Put the slowest reaction at the top and the fastest at the bottom.

b. Compare the trend in reaction rate with the trend in ionization energy while coming down the group.

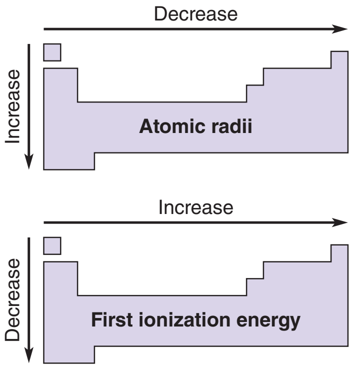
c. Compare the trend in reaction rate coming down the group with the trend in ease of removing an electron from an atom of the metal coming down the group.

The trends in ionization energy and ease of removing an electron can be explained using arguments similar to those for explaining the sizes of atoms. As we move down a group, the valence electrons are located farther and farther away from the nucleus because they are located in higher-energy shells. The farther the electrons from the nucleus, the weaker is the attraction of the positively charged nucleus towards the negatively charged electrons, and the easier it is to pull the electrons away.

Similarly, as we go from left to right in a period, the valence electrons are going into the same shell and therefore are located at the same distance from the nucleus. But as we saw before, that the nuclear charge increases as well as the number of electrons. As a result, there is a greater nuclear charge attracting the electrons the farther we move to the right. Thus, a valence electron of an atom farther to the right is more difficult to remove than a valence electron of an atom farther to the left.

The general trends we have discussed are summarized in **Figure 3.22**. It is easier to remember the trends by always going in the same direction in the table and noting how the properties change in that direction. We have chosen to summarize by always going from top to bottom for groups, and left to right for periods.

FIGURE 3.22 General trends for atomic size and ionization energy of representative elements.



Health Career Description

RADIOLOGIC TECHNICIAN/RADIOLOGIST

X-rays are made by electromagnetic radiation; knowledge of atomic particles and their properties is fundamental to the study of radiology. Some radiological images require contrast materials such as barium or iodine preparations. Therefore, knowledge of chemistry is important for people working in imaging. Radiologists study chemistry to understand its role in human physiology, a subject they must understand thoroughly.

Radiologists must be skilled not only in producing quality images through correct patient positioning and use of appropriate machinery, but they must also interact with patients and their families. They are expected to deliver information to patients and families in a clear, informative, and understanding manner. Radiologists are expected to keep accurate records and follow all privacy laws.

Radiologists use sterile techniques in the event of a traumatic injury or when conducting invasive procedures. They must understand and adhere to radiation protection guidelines. Radiologists must be able to recognize emergent patient conditions and respond quickly and appropriately, especially if cardiac or pulmonary complications arise.

A job listing for Johns Hopkins Bayview Medical Center, describes the expectations for a radiological technician in this way, "Under minimal supervision, operates standard, portable, and specialized X-ray equipment to perform radiographic examinations used for diagnosis and treatment. Provides appropriate patient care, develops film and instructs radiology students as needed. Diagnostic Imaging includes OR, Ortho, ED and Fluoro procedures."

Radiologic technicians require state licensure to practice. "Radiologic technicians" require certification at an associate degree level, whereas "radiologists" practice at a bachelor degree level. Radiologists may continue through to a master's degree level. Imaging technicians are expected to continue their education and to remain familiar with emerging technology and techniques. They may be called on to teach student workers. Professional radiologists occupy a place of trust in the community and help protect health by operating from within a specific body of scientific knowledge.

Concept Summary

3.1 The Periodic Law and Table

Learning Objective: Can you locate elements in the periodic table on the basis of group and period designations?

- The chemical properties of the elements tend to repeat in a regular (periodic) way when the elements are arranged in order of increasing atomic numbers.
- This periodic law is the basis for the arrangement of the elements called the periodic table.
- In this table, each element belongs to a vertical grouping called a group or family.
- Each element belongs to a horizontal grouping called a period.
- All elements in a group or family have similar chemical properties.

3.2 Electronic Arrangements in Atoms

Learning Objective: Can you determine the number of electrons in designated atomic orbitals, subshells, or shells?

- Niels Bohr proposed a theory for the electronic structure of hydrogen based on the idea that the electrons of atoms move around atomic nuclei in fixed circular orbits.
- Electrons change orbits only when they absorb or release energy.
- The Bohr model was modified as a result of continued research.
- It was found that precise Bohr orbits for electrons could not be determined.
- Instead, the energy and location of electrons could be specified in terms of shells, subshells, and orbitals.
- These are indicated by a notation system of numbers and letters.

3.3 The Shell Model and Chemical Properties

Learning Objective: Can you determine the number of valence shell electrons and the electronic structure for atoms, and relate this information to the location of elements in the periodic table?

- The modified Bohr model, or shell model, of electronic structure provides an explanation for the periodic law.
- The rules governing electron occupancy in shells, subshells, and orbitals result in a repeating pattern of valence shell electron arrangements.
- Elements with similar chemical properties turn out to be elements with identical numbers and types of electrons in their valence shells.

3.4 Electronic Configurations

Learning Objective: Can you determine the following for elements: the electronic configuration of atoms, the number of unpaired electrons in atoms, and the identification of atoms based on provided electronic configurations?

- The arrangements of electrons in orbitals, subshells, and shells are called electronic configurations.
- Rules and patterns have been found that allow these configurations to be represented in a concise way.
- Written electronic configurations allow details of individual orbital, subshell, and shell electron occupancies to be seen readily.
- The number of unpaired electrons in elements is easily determined.
- Electronic configurations can be represented in an abbreviated form by using noble gas symbols to represent some of the inner electrons.

3.5 Another Look at the Periodic Table

Learning Objective: Can you determine the shell and subshell locations of the distinguishing electrons in elements, and based on their location in the periodic table, classify elements into the categories given in Figures 3.13 and 3.16?

- Correlations between electronic configurations for the elements and the periodic table arrangement of elements make it possible to determine a number of details of electronic structure for an element simply on the basis of the location of the element in the periodic table.
- Special attention is paid to the last or distinguishing electron in an element.
- Elements are classified according to the type of subshell (*s, p, d, f*) occupied by this electron.
- The elements are also classified on the basis of other properties as metals, nonmetals, or metalloids.

3.6 Property Trends within the Periodic Table

Learning Objective: Can you recognize property trends of elements within the periodic table, and use the trends to predict selected properties of the elements?

- Chemical and physical properties of elements follow trends within the periodic table.
- These trends are described in terms of changes in properties of elements from the top to the bottom of groups, and from the left to the right of periods.
- The sizes of atoms and first ionization energies are two properties that show distinct trends.

Key Terms and Concepts

Atomic orbital (3.2)
Distinguishing electron (3.5)
Electronic configurations (3.4)
First ionization energy (3.6)
Group or family of the periodic table (3.1)
Hund's rule (3.4)
Inner-transition element (3.5)
Metals (3.5)
Metalloids (3.5)
Noble gas configuration (3.4)
Nonmetals (3.5)
Pauli exclusion principle (3.4)
Periodic law (3.1)
Period of the periodic table (3.1)
Representative element (3.5)
Shell (3.2)
Subshell (3.2)
Transition element (3.5)
Valence shell (3.3)

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

The Periodic Law and Table (Section 3.1)

3.1 Identify the group and period to which each of the following elements belongs:

a. Si

b. element number 21

c. zinc

d. element number 35

3.2 Identify the group and period to which each of the following elements belongs:

a. element number 27

b. Pb

c. arsenic

d. Ba

3.3 Write the symbol and name for the elements located in the periodic table as follows:

a. Belongs to group VIA(16) and period 3

b. The first element (reading down) in group VIB(6)

c. The fourth element (reading left to right) in period 3

d. Belongs to group IB(11) and period 5

3.4 Write the symbol and name for the elements located in the periodic table as follows:

a. The noble gas belonging to period 4

b. The fourth element (reading down) in group IVA(14)

c. Belongs to group VIB(6) and period 5

d. The sixth element (reading left to right) in period 6

3.5 **a.** How many elements are located in group VIIB(7) of the periodic table?

b. How many elements are found in period 5 of the periodic table?

c. How many total elements are in groups IVA(14) and IVB(4) of the periodic table?

3.6 **a.** How many elements are located in group VIIB(7) of the periodic table?

b. How many total elements are found in period 1 and 2 of the periodic table?

c. How many elements are found in period 5 of the periodic table?

3.7 The following statements either define or are closely related to the terms *periodic law*, *period*, and *group*. Match the terms to the appropriate statements.

a. This is a vertical arrangement of elements in the periodic table.

b. The chemical properties of the elements repeat in a regular way as the atomic numbers increase.

c. The chemical properties of elements 11, 19, and 37 demonstrate this principle.

d. Elements 4 and 12 belong to this arrangement.

3.8 The following statements either define or are closely related to the terms *periodic law*, *period*, and *group*. Match the terms to the appropriate statements.

a. This is a horizontal arrangement of elements in the periodic table.

b. Element 11 begins this arrangement in the periodic table.

c. The element nitrogen is the first member of this arrangement.

d. Elements 9, 17, 35, and 53 belong to this arrangement.

Electronic Arrangements in Atoms (Section 3.2)

3.9 According to the Bohr theory, which of the following would have the higher energy?

a. An electron in an orbit close to the nucleus

b. An electron in an orbit located farther from the nucleus

3.10 What particles in the nucleus cause the nucleus to have a positive charge?

3.11 What is the maximum number of electrons that can be contained in each of the following?

a. A 3*d* orbital

b. A 3*d* subshell

c. The third shell

3.12 What is the maximum number of electrons that can be contained in each of the following?

a. A 2*p* orbital

b. A 2*p* subshell

c. The second shell

3.13 How many orbitals are found in the fourth shell? Write designations for the orbitals.

3.14 How many orbitals are found in the second shell? Write designations for the orbitals.

3.15 How many orbitals are found in a 3*d* subshell? What is the maximum number of electrons that can be accomodated in this subshell?

3.16 How many orbitals are found in 4*f* subshell? What is the maximum number of electrons that can be located in this subshell?

3.17 Identify the subshells found in the fourth shell; indicate the maximum number of electrons that can occupy each subshell and the total number of electrons that can occupy the shell.

The Shell Model and Chemical Properties (Section 3.3)

3.18 Look at the periodic table and tell how many electrons are in the valence shell of the following elements:

a. element number 54

b. the first element (reading down) in group VA(15)

c. Sn

d. The fourth element (reading left to right) in period 3

3.19 Look at the periodic table and tell how many electrons are in the valence shell of the following elements:

a. element number 35

b. Zn

c. strontium

d. the second element of group VA(15)

3.20 Which period 6 element has chemical properties most like to that of sodium? How many valence-shell electrons does this element have? How many valence-shell electrons does sodium have?

3.21 Which period 5 element has chemical properties most like to that of silicon? How many valence shell electrons does this element have? How many valence shell electrons does silicon have?

3.22 If you discover an ore deposit containing copper, which other two elements might you also expect to find in the ore? Explain your reasoning completely.

3.23 Radioactive isotopes of strontium were produced by the explosion of nuclear weapons. They were considered serious health hazardous because they were incorporated into the bones of animals that ingested them. Explain why strontium would be likely to be deposited in bones.

Electronic Configurations (Section 3.4)

3.24 Write an electronic configuration for each of the following elements, using the form $1s^22s^22p^6$, and so on. Indicate how many electrons are unpaired in each case.

a. element number 37

b. Si

c. titanium

d. Ar

3.25 Write an electronic configuration for each of the following elements, using the form $1s^22s^22p^6$, and so on. Indicate how many of the electrons are unpaired in each case.

a. K

b. manganese

c. element number 33

d. Ti

3.26 Write electronic configurations and answer the following:

a. How many total *s* electrons are found in magnesium?

b. How many unpaired electrons are in nitrogen?

c. How many subshells are completely filled in Al?

3.27 Write electronic configurations and answer the following:

- **a.** How many total electrons in Ge have a number designation (before the letters) of 4?
- **b.** How many unpaired *p* electrons are found in sulfur? What is the number designation of these unpaired electrons?
- **c.** How many 3*d* electrons are found in tin?

3.28 Write the symbol and name for each of the elements described. More than one element will fit some descriptions.

- **a.** Contains only two 2*p* electrons
- **b.** Contains an unpaired 3*s* electron
- **c.** Contains two unpaired 3*p* electrons
- **d.** Contains three 4*d* electrons
- **e.** Contains three unpaired 3*d* electrons

3.29 Write the symbol and name for each of the elements described. More than one element will fit some descriptions.

- **a.** Contains one unpaired 5*p* electron
- **b.** Contains a half-filled 5*s* subshell
- **c.** Contains a half-filled 6*p* subshell
- **d.** The last electron completes the 4*d* subshell
- **e.** The last electron half fills the 4*f* subshell

3.30 Write abbreviated electronic configurations for the following:

- **a.** arsenic
- **b.** an element that contains 25 electrons
- **c.** silicon
- **d.** element number 53

3.31 Write abbreviated electronic configurations for the following:

- **a.** an element that contains 24 electrons
- **b.** element number 21
- **c.** iodine
- **d.** copper

3.32 Refer to the periodic table and write abbreviated electronic configurations for all elements in which the noble gas symbol used will be [Ne].

3.33 Refer to the periodic table and determine how many elements have the symbol [Kr] in their abbreviated electronic configurations.

Another Look at the Periodic Table (Section 3.5)

3.34 Classify each of the following elements into the *s*, *p*, *d*, or *f* area of the periodic table on the basis of the distinguishing electron:

- **a.** lead, a poison to many organisms
- **b.** element 27, used in detection of tumors and metastases
- **c.** Tb, radioactive isotope used to treat cancer
- **d.** Rb, used in PET scans to help diagnose heart disease

3.35 Classify each of the following elements into the *s*, *p*, *d*, or *f* area of the periodic table on the basis of the distinguishing electron:

- **a.** Kr, radioactive isotope used in heart shunt studies
- **b.** tin, although not well researched, some people take by mouth for cancer
- **c.** Pu, is used to power heart pacemakers
- **d.** element 40, used in the manufacture of prosthetics

3.36 Classify the following elements as representative, transition, inner-transition, or noble gases:

- **a.** iron, found in hemoglobin
- **b.** element 15, found in bones, ATP, DNA, and many other biological materials
- **c.** U, radioactive isotopes used for medical diagnosis and research
- **d.** bismuth, used in an antacid medication

3.37 Classify the following elements as representative, transition, inner-transition, or noble gases:

- **a.** W, used in oncology treatment instruments
- **b.** Cm, used in medical power sources
- **c.** element 10, used as a diagnostic tracer in lung diffusion tests
- **d.** helium, used in MRI cooling systems
- **e.** barium, sulfate used in digestive system CT scans

3.38 Classify the following as metals, nonmetals, or metalloids:

- **a.** argon, used in a cauterizing surgical tool
- **b.** element 3, used to help treat bipolar disorder
- **c.** Ge, despite serious safety concerns, some people use it as a medicine
- **d.** boron, essential for growth and maintenance of bone
- **e.** Pm, may be used in pacemakers

3.39 Classify the following as metals, nonmetals, or metalloids:

- **a.** rubidium, used in positron-emission tomographic (PET) scans to help diagnose heart disease
- **b.** arsenic, despite safety concerns, it is used in some diluted homeopathic remedies
- **c.** element 49, radioactive isotope is used in nuclear medicine tests
- **d.** S, the third most abundant mineral in the human body
- **e.** Br, ions used in sedatives, anti-epileptics, and tranquillizers

Property Trends within the Periodic Table (Section 3.6)

3.40 Use trends within the periodic table to predict which member of each of the following pairs is more metallic:

- **a.** K or Ti
- **b.** As or Bi
- **c.** Mg or Sr
- **d.** Sn or Ge

3.41 Use trends within the periodic table to predict which member of each of the following pairs is more metallic:

- **a.** C or Sn
- **b.** Sb or In
- **c.** Ca or As
- **d.** Al or Mg

3.42 Use trends within the periodic table and indicate which member of each of the following pairs has the larger atomic radius:

- **a.** Ga or Se
- **b.** N or Sb
- **c.** O or C
- **d.** Te or S

3.43 Use trends within the periodic table and indicate which member of each of the following pairs has the larger atomic radius:

- **a.** Mg or Sr
- **b.** Rb or Ca
- **c.** S or Te
- **d.** I or Sn

3.44 Use trends within the periodic table and indicate which member of each of the following pairs gives up one electron more easily:

- **a.** Li or K
- **b.** C or Sn
- **c.** Mg or S
- **d.** Li or N

3.45 Use trends within the periodic table and indicate which member of each of the following pairs gives up one electron more easily:

- **a.** Mg or Al
- **b.** Ca or Be
- **c.** S or Al
- **d.** Te or O

Additional Exercises

3.46 How would you expect the chemical properties of isotopes of the same element to compare to each other? Explain your answer.

3.47 Bromine (Br) and mercury (Hg) are the only elements that are liquids at room temperature. All other elements in the periodic group that contains mercury are solids. Explain why mercury and bromine are not in the same group.

3.48 What would be the mass in mg of 3.0×10^{20} atoms that all have the same electronic configuration of $1s^2\ 2s^2\ 2p^4$?

3.49 Refer to **Figure 3.19** and predict what would happen to the density of the metallic elements (purple color) as you go from left to right across a period of the periodic table. Explain your reasoning.

3.50 A 10.02-g sample of an element contains 0.250 mol of the element. Classify the element into the correct category of representative, transition, inner-transition, or noble gas. Will the element conduct electricity?

Chemistry for Thought

3.51 Samples of three metals that belong to the same group of the periodic table are shown in **Figure 3.6**. When magnesium reacts with bromine, a compound with the formula $MgBr_2$ results. What would be the formulas of the compounds formed by reactions of bromine with each of the other metals shown? Explain your reasoning.

3.52 Answer the problem posed in **Figure 3.18**, then predict the same things for fluorine, the first member of the group. Explain the reasoning that led you to your answers.

3.53 Answer the problem posed in **Figure 3.14**. What property that makes gold suitable for coins and medals also makes it useful in electrical connectors for critical electronic parts such as computers in spacecraft?

3.54 Calcium metal reacts with cold water as follows:

$$Ca + 2H_2O \rightarrow Ca(OH)_2 + H_2$$

Magnesium metal does not react with cold water. What behavior toward cold water would you predict for strontium and barium? Write equations to represent any predicted reactions.

3.55 Refer to the hotels analogy in Study Skills 3.1 and determine the number of floors and the number of rooms on the top floor of Hotel Five.

3.56 A special sand is used by a company as a raw material. The company produces zirconium metal that is used to contain the fuel in nuclear reactors. What other metals are likely to be produced from the same raw material? Explain your answer.

4 Forces between Particles

LightField Studios/Shutterstock.com

Health Career Focus

PARAMEDIC

I love an adrenaline rush—maybe that explains my obsession with watching and playing sports. Choosing between coaching and a science major was a tough decision. My academic advisor suggested I take a "strengths test." It paired my interests and strengths with possible careers. When the results suggested "paramedic," I wondered why I hadn't thought of that—it fit me perfectly! I love helping people and solving problems as well as working under pressure.

I scheduled a tour of the paramedic program at my local community college. Their "lab" was an actual ambulance! I liked the idea that I could use my physical strength in emergency situations. My interest in physics, chemistry, and anatomy mesh well with this career. I thrive in the high-stress environment. We respond to accidents, overdoses, and cardiac events; we make split-second decisions. Working as a paramedic is never boring!

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Draw correct Lewis structures for atoms of representative elements. **(Section 4.1)**
2. Use electronic configurations to determine the number of electrons gained or lost by atoms as they achieve noble gas electronic configurations. **(Section 4.2)**
3. Use the octet rule to correctly predict the ions formed during the formation of ionic compounds, and write correct formulas for binary ionic compounds containing a representative metal and a representative nonmetal. **(Section 4.3)**
4. Correctly name binary ionic compounds. **(Section 4.4)**
5. Determine formula weights for ionic compounds. **(Section 4.5)**
6. Draw correct Lewis structures for covalent molecules. **(Section 4.6)**
7. Draw correct Lewis structures for polyatomic ions. **(Section 4.7)**
8. Use VSEPR theory to predict the shapes of molecules and polyatomic ions. **(Section 4.8)**
9. Use electronegativities to classify covalent bonds of molecules, and determine whether covalent molecules are polar or nonpolar. **(Section 4.9)**

10 Write correct formulas for ionic compounds containing representative metals and polyatomic ions, and correctly name binary covalent compounds and compounds containing polyatomic ions. **(Section 4.10)**

11 Relate melting and boiling points of pure substances to the strength and type of interparticle forces present in the substances. **(Section 4.11)**

IN THE DISCUSSION TO this point, we have emphasized that matter is composed of tiny particles. However, we have not yet discussed the forces that hold these particles together to form the matter familiar to us. It is these forces that produce many of the properties associated with various types of matter—properties such as the electrical conductivity of copper wire, the melting point of butter, and the boiling point of water.

4.1 Noble Gas Configurations

Learning Objective 1 Draw correct Lewis structures for atoms of representative elements.

The octet rule, proposed in 1916 by G. N. Lewis (an American) and Walther Kossel (a German), was the first widely accepted theory to describe bonding between atoms. The basis for the rule was the observed chemical stability of the noble gases. Because the noble gases did not react readily with other substances and because chemical reactivity depends on electronic structure, chemists concluded that the electronic structure of the noble gases represent a stable (low-energy) configuration. This noble gas configuration (see **Section 3.4**) is characterized by two electrons in the valence shell of helium (see **Figure 4.1**) and eight valence-shell electrons for the other members of the group (Ne, Ar, Kr, Xe, and Rn).

izusek/E+/Getty Images

FIGURE 4.1 Liquid helium is used in cooling the magnets of MRI (magnetic resonance imaging) scanners to a temperature below 10 K.

Example 4.1 Working with Electronic Configurations

Use the techniques described in **Section 3.4** to write the electronic configurations for the noble gases. Identify the valence-shell electrons, and verify the noble gas configurations just mentioned.

Solution

The subshell-filling order in **Figure 3.9** gives the electronic configurations shown below. Valence-shell electrons are in darker type, and the noble gas configurations are verified.

Noble Gas	Electronic Configuration	Number of Valence-Shell Electrons
He:	$\mathbf{1s^{2}}$	2
Ne:	$1s^{2}\mathbf{2s^{2}2p^{6}}$	8
Ar:	$1s^{2}2s^{2}2p^{6}\mathbf{3s^{2}3p^{6}}$	8
Kr:	$1s^{2}2s^{2}2p^{6}3s^{2}3p^{6}\mathbf{4s^{2}}3d^{10}\mathbf{4p^{6}}$	8
Xe:	$1s^{2}2s^{2}2p^{6}3s^{2}3p^{6}4s^{2}3d^{10}4p^{6}\mathbf{5s^{2}}4d^{10}\mathbf{5p^{6}}$	8
Rn:	$1s^{2}2s^{2}2p^{6}3s^{2}3p^{6}4s^{2}3d^{10}4p^{6}5s^{2}4d^{10}5p^{6}\mathbf{6s^{2}}4f^{14}5d^{10}\mathbf{6p^{6}}$	8

✔ **LEARNING CHECK 4.1** Write the electronic configurations for F and K. What would have to be done to change these configurations to noble gas configurations (how many electrons would have to be added or removed)?

Lewis structure A representation of an atom or ion in which the elemental symbol represents the atomic nucleus and all but the valence-shell electrons. The valence-shell electrons are represented by dots arranged around the elemental symbol.

A simplified way to represent the valence-shell electrons of atoms was invented by G. N. Lewis (see **Figure 4.2**). In these representations, called electron-dot formulas or **Lewis structures**, the symbol for an element represents the nucleus and all electrons around the nucleus except those in the valence shell. Valence-shell electrons are shown as dots around the symbol. Thus, rubidium is represented as Rb·.

When a Lewis structure is written for an element, it is necessary to determine the number of valence-shell electrons in the element. This can be done by writing the electronic configuration using the methods described in Chapter 3 and identifying the valence-shell electrons as those with the highest *n* value. A simpler alternative for representative elements is to refer to the periodic table and note that the number of valence-shell electrons in the atoms of an element is the same as the number of the group in the periodic table to which the element belongs. The group number used must be the one that precedes the letter A, not the one in parentheses as given in the periodic table inside the front cover of this book. Using this method, we see that rubidium belongs to group IA(1) and therefore has one valence-shell electron.

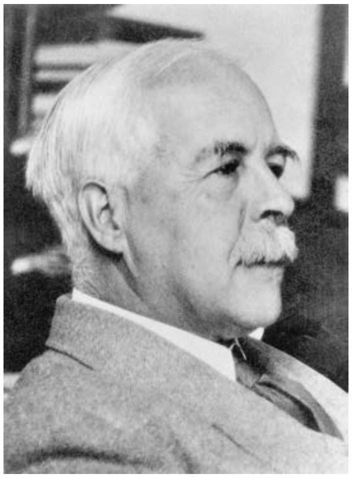

Bettmann/Getty Images

FIGURE 4.2 G. N. Lewis was nominated for the Nobel Prize 35 times, but he never won.

Example 4.2 Drawing Lewis Structures

Draw Lewis structures for atoms of the following:

a. element number 4
b. cesium (Cs)
c. aluminum (Al)
d. selenium (Se)

The accepted procedure is to write the element's symbol and put a dot for each valence electron in one of four equally spaced locations around the symbol. Imagine a square around the symbol. Each side of the square represents one of the four locations. An element with four valence electrons would have one dot in each of the four locations. A fifth electron would be represented by one additional dot in one of the locations. Each location can have a maximum of two dots.

Solution

a. Element number 4 is beryllium; it belongs to group IIA(2) and thus has two valence-shell electrons. The Lewis structure is $\underset{\cdot}{\mathrm{Be}}\cdot$.
b. Cesium is in group IA(1), has one valence-shell electron, and has the Lewis structure Cs·.
c. Aluminum is in group IIIA(13). It has three valence-shell electrons and is represented by the following Lewis structure: $\overset{\cdot}{\underset{\cdot}{\mathrm{Al}}}\cdot$.
d. Selenium is in group VIA(16) and thus has six valence-shell electrons. The Lewis structure is $:\overset{\cdot\cdot}{\underset{\cdot}{\mathrm{Se}}}\cdot$.

✔ **LEARNING CHECK 4.2** Draw Lewis structures for atoms of the following:

a. element number 9
b. magnesium (Mg)
c. sulfur (S)
d. krypton (Kr)

It is important to clearly understand the relationship between Lewis structures and electronic configurations for atoms. The following example and learning check will help you review this relationship.

Example 4.3 Using Abbreviated Electronic Configurations

Compounds of fluorine (F) are used in toothpaste and in drinking water to prevent dental cavities.

Represent the following using abbreviated electronic configurations and Lewis structures:

a. F b. K c. Mg d. Si

Solution

a. Fluorine (F) contains nine electrons, with seven of them classified as valence electrons (those in the 2*s* and 2*p* subshells). The configuration and Lewis structure are

$$[\mathrm{He}]2s^22p^5 \qquad \text{and} \qquad :\underset{\cdot\cdot}{\overset{\cdot\cdot}{\mathrm{F}}}\cdot$$

b. Potassium (K) contains nineteen electrons, with one of them classified as a valence electron (the one in the 4*s* subshell). The configuration and Lewis structure are

$$[\mathrm{Ar}]4s^1 \qquad \text{and} \qquad \mathrm{K}\cdot$$

c. Magnesium (Mg) contains twelve electrons, with two of them classified as valence electrons (the two in the 3*s* subshell). The configuration and Lewis structure are

$$[\mathrm{Ne}]3s^2 \qquad \text{and} \qquad \dot{\mathrm{M}}\mathrm{g}\cdot$$

d. Silicon (Si) contains fourteen electrons, with four of them classified as valence electrons (those in the 3*s* and 3*p* subshells). The configuration and Lewis structure are

$$[\mathrm{Ne}]3s^23p^2 \qquad \text{and} \qquad \cdot\underset{\cdot}{\overset{\cdot}{\mathrm{Si}}}\cdot$$

✔ **LEARNING CHECK 4.3** Using the two methods illustrated in Example 4.3, write electronic configurations and Lewis structures for the following atoms:

a. Li b. Br c. Sr d. S

4.2 Ionic Bonding

Learning Objective 2 Use electronic configurations to determine the number of electrons gained or lost by atoms as they achieve noble gas electronic configurations.

According to the **octet rule** of Lewis and Kossel (see **Figure 4.3**), atoms tend to interact through electronic rearrangements that produce a noble gas electronic configuration for each atom involved in the interaction. Except for the lowest-energy shell, this means that each atom ends up with eight electrons in the valence shell. There are exceptions to this octet rule, but it is still used because of the amount of information it provides. It is especially effective in describing reactions between the representative elements of the periodic table (see **Figure 3.13**).

During some chemical interactions, the octet rule is satisfied when electrons are transferred from one atom to another. As a result of the transfers, neutral atoms acquire net positive or negative electrical charges and become attracted to one another. These charged atoms are called **simple ions**, and the attractive force between oppositely charged atoms constitutes an **ionic bond**. A second type of interaction that also satisfies the octet rule is discussed in **Section 4.6**.

Fine Art Images/Heritage Image Partnership Ltd/Alamy Stock Photo

FIGURE 4.3 Walther Kossel, a German physicist, proposed the octet rule the same year (1916) that G. N. Lewis did.

octet rule A rule for predicting electron behavior in reacting atoms. It says that atoms will gain or lose sufficient electrons to achieve an outer electron arrangement identical to that of a noble gas. This arrangement usually consists of eight electrons in the valence shell.

simple ion An atom that has acquired a net positive or negative charge by losing or gaining electrons.

ionic bond The attractive force that holds together ions of opposite charge.

Example 4.4 Ions and Noble Gas Configurations

Show how the following atoms can achieve a noble gas configuration and become ions by gaining or losing electrons:

a. Na b. Cl

Solution

a. The electronic structure of sodium (Na) is represented below using an abbreviated configuration and a Lewis structure:

$$[\mathrm{Ne}]3s^1 \qquad \text{and} \qquad \mathrm{Na}\cdot$$

The first representation makes it obvious that the Ne configuration with 8 electrons in the valence shell would result, if the Na atom lost the single electron located in the 3*s* subshell. The loss is represented by the following equation:

$$\mathrm{Na} \rightarrow \mathrm{Na}^+ + 1e^-$$

Notice that the removal of a single negative electron from a neutral Na atom leaves the atom with 11 positive protons in the nucleus and 10 negative electrons. This gives the atom a net positive charge. The atom has become a positive ion.

b. The electronic structure for chlorine (Cl) is shown below using an abbreviated configuration and a Lewis structure:

$$[\mathrm{Ne}]3s^2 3p^5 \qquad \text{and} \qquad :\!\ddot{\underset{\cdot\cdot}{\mathrm{Cl}}}\!\cdot$$

The Cl atom can achieve an Ne configuration by losing the 7 valence electrons. However, it is energetically much more favorable to achieve the configuration of argon (Ar) by adding 1 electron to the valence shell. This electron would complete an octet and change a Cl atom into a negative chloride ion as represented by the following equation, where Cl^- represents a Cl atom with 17 protons and 18 electrons, giving the atom a net negative charge:

$$\mathrm{Cl} + 1e^- \rightarrow \mathrm{Cl}^-$$

✔ **LEARNING CHECK 4.4** In Learning Check 4.1, you described what had to be done to change the electronic configurations of F and K to achieve noble gas configurations. Write equations to illustrate these changes.

As a general rule, metals lose electrons (see **Figure 4.4**) and nonmetals gain electrons during ionic bond formation. The number of electrons lost or gained by a single atom rarely exceeds three, and this number can be predicted accurately for representative elements by using the periodic table. The number of electrons easily lost by a representative metal atom is the same as the group number (represented by Roman numerals preceding the A in the periodic table). The number of electrons that tend to be gained by a representative nonmetal atom is equal to eight minus the group number. However, the nonmetal hydrogen is an exception. In most reactions, it loses one electron, consistent with its placement in group IA(1). In other less common reactions, it gains one electron just as group VIIA(17) elements do.

Nutrition Facts
Serving Size 2/3 cup (51g)
Servings Per Container About 9
Amount Per Serving Cereal / Cereal with 1/2 cup Skim Milk
Calories 240 280
Calories from Fat 70 70
% Daily Value**
Total Fat 8g* 12% 12%
Saturated Fat 2.5g 13% 13%
Trans Fat 0g
Cholesterol 0mg 0% 0%
Sodium 50mg 2% 5%
Total Carbohydrate 37g 12% 14%
Dietary Fiber 3g 12% 12%
Sugars 13g
Protein 4g 8% 16%
Vitamin A 0% 4%
Vitamin C 0% 0%
Calcium 2% 15%
Iron 6% 6%

Chris Sadowski/E+/Getty Images

FIGURE 4.4 Acid in the stomach converts metallic iron (Fe), present in fortified cereals, into Fe^{2+} ions.

Example 4.5 Losing and Gaining Electrons

Use the periodic table to predict the number of electrons lost or gained by atoms of the following elements during ionic bond formation. Write an equation to represent the process in each case.

a. Li
b. Any group IIA(2) element, represented by the symbol M

c. element number 15
d. carbon

Solution

a. Lithium (Li), a metal, is in group IA(1); therefore it will lose one electron per atom:

$$\text{Li} \rightarrow \text{Li}^{+} + 1e^{-}$$

b. Any group IIA(2) metal will lose two electrons; therefore,

$$\text{M} \rightarrow \text{M}^{2+} + 2e^{-}$$

c. Element number 15 is phosphorus (P), a nonmetal of group VA(15). It will gain $(8 - 5) = 3$ electrons. The equation is

$$\text{P} + 3e^{-} \rightarrow \text{P}^{3-}$$

d. Carbon (C) is in group IVA(14) and is a nonmetal. It should, therefore, gain $(8 - 4) = 4$ electrons. However, no more than three electrons generally become involved in ionic bond formation, so we conclude that carbon will not react readily to form ionic bonds.

✔ **LEARNING CHECK 4.5** Predict the number of electrons that would be gained or lost during ionic bond formation for each of the following elements. Write an equation to represent each predicted change.

a. element number 34 b. Rb c. element number 18 d. In

While your attention is focused on noble gas configurations, it is appropriate to emphasize the following point: The attainment of a noble gas electronic configuration by an atom does not mean that the atom is converted into a noble gas. Instead, as seen above, the atoms are converted into simple ions (charged atoms). This point is emphasized by the comparison given in **Table 4.1**. Notice that the electronic configuration of Mg^{2+} is the same as that of Ne, but the number of protons (the atomic number) of Mg^{2+} is still the same as that of Mg. Atoms and simple ions that have identical electronic configurations are said to be **isoelectronic**.

isoelectronic A term that literally means "same electronic," is used to describe atoms or ions that have identical electronic configurations.

TABLE 4.1 A Metal Atom, a Metal Ion, and a Noble Gas Atom Compared

Particle	Symbol	Number of Protons in Nucleus	Number of Electrons around Nucleus	Net Charge on Particle
Magnesium atom	Mg	12	12	0
Magnesium ion	Mg^{2+}	12	10	+2
Neon atom	Ne	10	10	0

4.3 Ionic Compounds

Learning Objective 3 Use the octet rule to correctly predict the ions formed during the formation of ionic compounds, and write correct formulas for binary ionic compounds containing a representative metal and a representative nonmetal.

So far the discussion has focused on the electron-transfer process as it occurs for isolated atoms. In reality, the electrons lost by a metal are the same ones gained by the nonmetal with which it is reacting. Substances formed from such reactions are called *ionic* *compounds*. No atom can lose electrons unless another atom is available to accept them, as shown in the formulas used to represent ionic compounds. These formulas represent the combining ratio of the positive and negative ions found in the compounds. This ratio is determined by the charges on the ions, which are determined by the number of electrons transferred.

Example 4.6 Electron Transfer Processes

Represent the electron-transfer process that takes place when the following pairs of elements react ionically. Determine the formula for each resulting ionic compound.

a. Na and Cl b. Mg and F

Solution

a. Sodium (Na) is in group IA(1), and we can write:

$$\mathrm{Na} \rightarrow \mathrm{Na}^+ + 1e^-$$

Chlorine (Cl), in group VIIA(17), reacts as follows:

$$\mathrm{Cl} + 1e^- \rightarrow \mathrm{Cl}^-$$

The resulting ions, Na^+ and Cl^-, will combine in a 1:1 ratio because the total positive and total negative charges in the final formula must add up to zero, resulting in the formation of NaCl. Note that the metal is written first in the formula, a generally followed practice. Also, the formula is written using the smallest number of each ion possible—in this case, one of each.

The actual electron-transfer process and the achievement of octets can more easily be visualized as follows:

$$\underset{\mathrm{[Ne]}3s^1}{\mathrm{Na}} + \underset{\mathrm{[Ne]}3s^23p^5}{\mathrm{Cl}} \rightarrow \underset{\mathrm{[Ne]}}{\mathrm{Na}^+} + \underset{\mathrm{[Ne]}3s^23p^6}{\mathrm{Cl}^-}$$

In this representation, it must be remembered that the $[Ne]3s^23p^6$ electronic configuration of Cl^- is the same configuration as argon, the noble gas that follows chlorine in the periodic table.

b. Magnesium (Mg) of group IIA(2) will lose two electrons per atom, whereas fluorine (F) of group VIIA(17) will gain one electron per atom. Therefore, we can write

$$\mathrm{Mg} \rightarrow \mathrm{Mg}^{2+} + 2e^-$$
$$\mathrm{F} + 1e^- \rightarrow \mathrm{F}^-$$

It is apparent that two fluorine atoms will be required to accept the electrons from one magnesium atom. From another point of view, two F^- ions will be needed to balance the charge of a single Mg^{2+} ion. Both observations lead to the formula MgF_2 for the compound. Note the use of subscripts to indicate the number of ions involved in the formula. The subscript 1, on Mg, is understood and never written.

✔ **LEARNING CHECK 4.6** Write equations to represent the formation of ions for each of the following pairs of elements. Write a formula for the ionic compound that would form in each case.

a. Mg and O b. K and S c. Ca and Br

binary compound A compound made up of two different elements.

Ionic compounds of the types used in Example 4.6 and Learning Check 4.6 are called **binary compounds** because each contains only two different kinds of atoms, Na and Cl in one case (see **Figure 4.5**) and Mg and F in the other.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS **4.1**

Consider the Mediterranean Diet

If you are looking for a heart-healthy eating plan, the Mediterranean diet might be right for you. The Mediterranean diet incorporates the basics of healthy eating—plus a splash of flavorful olive oil and perhaps even an occasional glass of red wine. These components characterize the traditional cooking style of countries that border the Mediterranean Sea.

Most healthful diets include fruits, vegetables, fish, and whole grains, and limit unhealthy fats. While these parts of a healthful diet remain tried and true, subtle variations or differences in the proportions of certain foods might make a difference in your risk for heart disease.

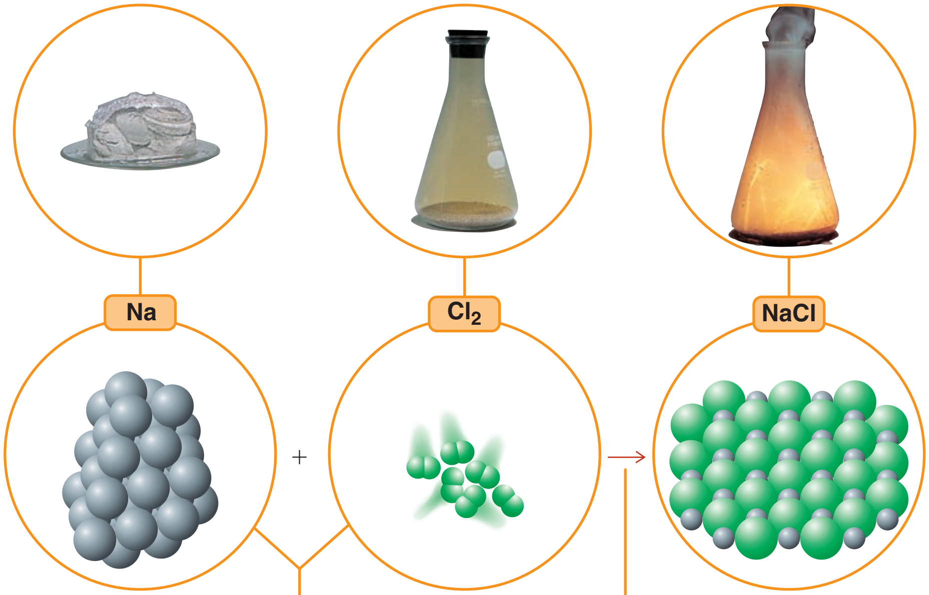
Research has shown that the traditional Mediterranean diet reduces the risk of heart disease. In fact, an analysis of more than 1.5 million healthy adults demonstrated that following a Mediterranean diet was associated with a reduced risk of death from heart disease and cancer, as well as a reduced incidence of Parkinson's and Alzheimer's diseases.

The Mediterranean diet emphasizes the following dietary practices:

1. Eating primarily plant-based foods, such as fruits, vegetables, whole grains, legumes, and nuts.
2. Replacing butter with healthy fats such as olive oil.
3. Using herbs and spices instead of salt to flavor foods.
4. Limiting red meat to no more than a few times a month.
5. Eating fish and poultry at least twice a week.
6. Drinking red wine in moderation (optional).

YuliiaHolovchenko/Shutterstock.com

The Mediterranean diet incorporates a variety of healthy foods.



Sodium metal and chlorine gas.

The combination reaction of sodium and chlorine. This reaction releases significant amounts of energy.

FIGURE 4.5 The reaction of sodium metal and chlorine gas. The vigorous reaction releases energy that heats the flask contents to a high temperature. Would you expect a similar reaction to occur between potassium metal and fluorine gas?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

4.4 Naming Binary Ionic Compounds

Learning Objective 4 Correctly name binary ionic compounds.

Names for binary ionic compounds are easily assigned when the names of the two elements involved are known. The name of the metallic element is given first, followed by the stem of the nonmetallic elemental name to which the suffix *-ide* has been added.

name = metal + nonmetal stem + *-ide*

The stem of the name of a nonmetal is the name of the nonmetal with the ending dropped. **Table 4.2** gives the stem of the names of some common nonmetallic elements.

TABLE 4.2 Stem Names and Ion Formulas of Common Nonmetallic Elements

Element	Stem	Formula of Ion
Bromine	brom-	Br^-
Chlorine	chlor-	Cl^-
Fluorine	fluor-	F^-
Iodine	iod-	I^-
Nitrogen	nitr-	N^{3-}
Oxygen	ox-	O^{2-}
Phosphorus	phosph-	P^{3-}
Sulfur	sulf-	S^{2-}

Example 4.7 Naming Binary Ionic Compounds

Name the following binary ionic compounds:

a. KCl b. SrO c. Ca_3N_2

Solution

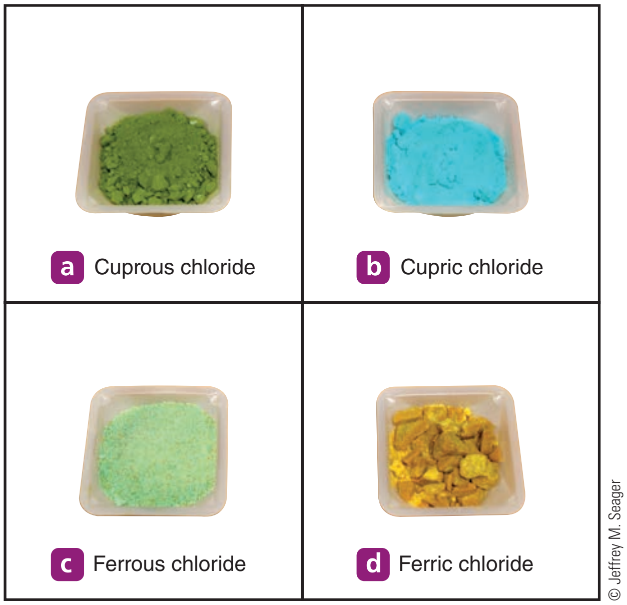
a. The metal is potassium (K), and the nonmetal is chlorine (Cl). Thus, the compound name is potassium chloride (the stem of the nonmetallic name is underlined). Potassium in ionic form is one of the most important minerals in the body, helping to regulate fluid balance, muscle contractions, and nerve signals.
b. Similarly, strontium (Sr) and oxygen (O) give the compound name strontium oxide.
c. The elements are calcium (Ca) and nitrogen (N), hence the name calcium nitride.

✔ **LEARNING CHECK 4.7** Assign names to the binary compounds whose formulas you wrote in Learning Check 4.6.

Names for the constituent ions of a binary compound are obtained in the same way as the compound name. Thus, K^+ is a potassium ion, whereas Cl^- is a chloride ion.

Some metal atoms, especially those of transition and inner-transition elements, form more than one type of charged ion. Copper, for example, forms both Cu^+ and Cu^{2+}, and iron forms Fe^{2+} and Fe^{3+}. The names of ionic compounds containing such elements must indicate which ion is present in the compound. A nomenclature system that does this well indicates the ionic charge of the metal ion by a Roman numeral in parentheses following the name of the metal. Thus, CuCl is copper(I) chloride and $CuCl_2$ is copper(II) chloride. These names are expressed verbally as "copper one chloride" and "copper two chloride."

An older system is still in use but works only for naming compounds of metals that can form only two different charged ions. In this method, the endings *-ous* and *-ic* are attached to the stem of the metal name. For metals with elemental symbols derived from non-English names, the stem of the non-English name is used. The *-ous* ending is always used with the ion of lower charge and the *-ic* ending with the ion of higher charge. Thus, CuCl is cuprous chloride, and $CuCl_2$ is cupric chloride. In the case of iron, $FeCl_2$ is ferrous chloride, and $FeCl_3$ is ferric chloride (see **Figure 4.6**). Notice that the Cu^{2+} ion was called cupric, whereas the Fe^{2+} was called ferrous. The designations do not tell the actual ionic charge, but only which of the two is higher (Cu^{2+} and Fe^{3+}) or lower (Cu^{+} and Fe^{2+}) for the metals in question.



© Jeffrey M. Seager

FIGURE 4.6 Chloride compounds of copper and iron. (a) Cuprous chloride. (b) Cupric chloride. (c) Ferrous chloride. (d) Ferric chloride.

Example 4.8 Formulas for Ionic Compounds

Write formulas for ionic compounds that would form between the following simple ions. Note that the metal forms two different simple ions, and name each compound two ways.

a. Cr^{2+} and S^{2-} b. Cr^{3+} and S^{2-}

Solution

In each case, the metal ion is from the metal chromium (Cr).

a. Because the ionic charges are equal in magnitude but opposite in sign, the ions will combine in a 1:1 ratio. The formula is CrS. Chromium forms simple ions with 2+ and 3+ charges. This one is 2+, the lower of the two; thus, the names are chromium(II) sulfide and chromous sulfide.

b. In this case, the charges on the combining ions are 3+ and 2−. The smallest combining ratio that balances the charges is two Cr^{3+} (a total of 6+ charge) and three S^{2-} (a total of 6− charge). The formula is Cr_2S_3. The names are chromium(III) sulfide and chromic sulfide.

✔ **LEARNING CHECK 4.8** Write formulas for the ionic compounds that would form between the following simple ions. The metal is cobalt, and it forms only two simple ions, as shown below. Name each compound, using two methods.

a. Co^{2+} and Br^{-} b. Co^{3+} and Br^{-}

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

4.5 The Smallest Unit of Ionic Compounds

Learning Objective 5 Determine formula weights for ionic compounds.

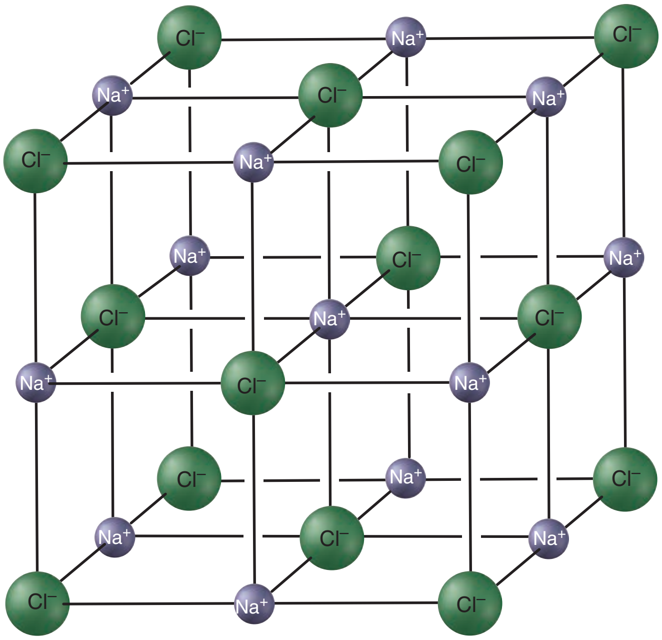
In **Section 1.3**, a molecule was defined as the smallest unit of a pure substance capable of a stable, independent existence. As you will see later, some compound formulas are used to represent single molecules. True molecular formulas represent the precise numbers of atoms of each element that are found in a molecule. However, as we have seen, formulas for ionic compounds represent only the simplest combining ratio of the ions in the compounds.

The stable form of an ionic compound is not a molecule, but a crystal in which many ions of opposite charge occupy **lattice sites** in a rigid three-dimensional arrangement called a **crystal lattice.** For example, the lattice of sodium chloride (ordinary table salt) represented in **Figure 4.7** is the stable form of pure sodium chloride.

lattice site The individual location occupied by a particle in a crystal lattice.

crystal lattice A rigid three-dimensional arrangement of particles.

FIGURE 4.7 Crystal lattice for sodium chloride (table salt).



Even though the formulas of ionic compounds do not represent true molecular formulas, they are often used as if they did. This is especially true when equations representing chemical reactions are written, or when the mole concept is applied to chemical formulas (see **Section 2.7**). When the atomic weights of the atoms making up a true molecular formula are added together, the result is called the molecular weight of the compound (see **Section 2.4**). A similar quantity obtained by adding up the atomic weights of the atoms shown in the formula of an ionic compound is called a **formula weight**. The mole concept is applied to formula weights in a manner similar to the way it is applied to molecular weights.

formula weight The sum of the atomic weights of the atoms shown in the formula of an ionic compound.

Example 4.9 Comparing Molecular and Ionic Compounds

Carbon dioxide, CO_2, is a molecular compound, whereas magnesium chloride, $MgCl_2$, is an ionic compound. Magnesium chloride is a mineral supplement used to prevent and treat low amounts of magnesium in the blood.

a. Determine the molecular weight for CO_2 and the formula weight for $MgCl_2$ in atomic mass units.
b. Determine the mass in grams of 1.00 mol of each compound.
c. Determine the number of CO_2 molecules in 1.00 mol and the number of Mg^{2+} and Cl^- ions in 1.00 mol of $MgCl_2$.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Solution

a. For CO_2, the molecular weight is the sum of the atomic weights of the atoms in the formula:

$$\text{MW} = (1)(\text{at. wt. C}) + (2)(\text{at. wt. O}) = (1)(12.0\ \text{u}) + (2)(16.0\ \text{u})$$
$$\text{MW} = 44.0\ \text{u}$$

For $MgCl_2$, the formula weight is also equal to the sum of the atomic weights of the atoms in the formula:

$$\text{FW} = (1)(\text{at. wt. Mg}) + (2)(\text{at. wt. Cl}) = (1)(24.3\ \text{u}) + (2)(35.5\ \text{u})$$
$$\text{FW} = 95.3\ \text{u}$$

b. According to **Section 2.6**, 1.00 mol of a molecular compound has a mass in grams equal to the molecular weight of the compound. Thus, 1.00 mol CO_2 = 44.0 g CO_2.

For ionic compounds, 1.00 mol of compound has a mass in grams equal to the formula weight of the compound. Thus, 1.00 mol $MgCl_2$ = 95.3 g $MgCl_2$.

c. In **Section 2.6** we learned that 1.00 mol of a molecular compound contains Avogadro's number of molecules. Thus, 1.00 mol $CO_2 = 6.02 \times 10^{23}$ molecules of CO_2.

In the case of ionic compounds, 1.00 mol of compound contains Avogadro's number of formula units. That is, 1.00 mol of magnesium chloride contains Avogadro's number of $MgCl_2$ units, where each unit represents one Mg^{2+} ion and two Cl^- ions. Thus,

$$1.00\ \text{mol}\ MgCl_2 = 6.02 \times 10^{23}\ MgCl_2\ \text{units}$$

or

$$1.00\ \text{mol}\ MgCl_2 = 6.02 \times 10^{23}\ Mg^{2+}\ \text{ions} + 1.20 \times 10^{24}\ Cl-\ \text{ions}$$

Note that the number of Cl^- ions is simply twice Avogadro's number.

✔ **LEARNING CHECK 4.9** Determine the same quantities that were determined in Example 4.9, but use the molecular compound hydrogen sulfide, H_2S, and the ionic compound calcium oxide, CaO.

4.6 Covalent Bonding

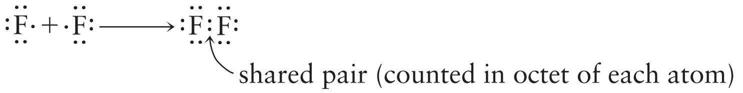
Learning Objective 6 Draw correct Lewis structures for covalent molecules.

StudioSmart/Shutterstock.com

FIGURE 4.8 Carbon compounds are the building blocks of the infinite variety of living forms.

In Example 4.5, we found that carbon, a nonmetal, would have to gain four electrons in order to form ionic bonds. We concluded that carbon does not generally form ionic bonds. Yet carbon is known to form many compounds with other elements (see **Figure 4.8**). Also, electron transfers would not be expected to take place between two atoms of the same element because such an exchange would not change the electronic configuration of the atoms involved. Yet molecules of elements containing two atoms, such as chlorine (Cl_2), oxygen (O_2), and nitrogen (N_2), are known to exist and, in fact, represent the stable form in which these elements occur in nature. What is the nature of the bonding in these molecules?

Again, G. N. Lewis provided an answer by suggesting that the valence-shell electrons of the atoms in such molecules are shared in a way that satisfies the octet rule for each of the atoms. This process is symbolized below for fluorine, (F_2), using Lewis structures:



Sometimes the shared electron pairs are shown as straight lines, and sometimes the nonshared pairs are not shown, as illustrated in Example 4.10.

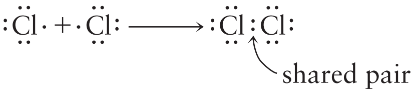
Example 4.10 Lewis Structures and Reactions

Represent the following reactions using Lewis structures:

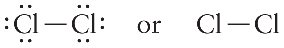
a. $Cl + Cl \rightarrow Cl_2$ b. $H + H \rightarrow H_2$

Solution

a. Each chlorine (Cl) atom has seven valence-shell electrons. Since one electron from each atom is shared, the octet rule is satisfied for each atom, as shown:



The structure of Cl_2 can also be represented as



b. Each hydrogen (H) atom has one valence-shell electron. By sharing the two electrons, each H atom achieves the helium (He) structure:

$$H\cdot + \cdot H \longrightarrow H:H \quad \text{or} \quad H-H$$

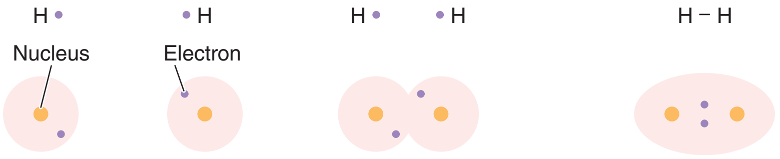
✔ LEARNING CHECK 4.10 Represent the following reactions using Lewis structures:

a. $N + N \rightarrow N_2$ (more than two electrons will be shared) b. $Br + Br \rightarrow Br_2$

To understand the origin of the attractive force between atoms that results from electron sharing, consider the H_2 molecule and the concept of atomic orbital overlap. Suppose two H atoms are moving toward each other. Each atom has a single electron in a spherical 1*s* orbital. While the atoms are separated, the orbitals are independent of each other; but as the atoms get closer together, the orbitals overlap and blend to create an orbital common to both atoms called a *molecular orbital*. The two shared electrons then move throughout the overlap region but have a high probability of being found somewhere between the two nuclei. As a result, both of the positive nuclei are attracted towards the negative pair of electrons and hence toward each other. This process, represented in **Figure 4.9**, produces a net attractive force between the nuclei. This attractive force is the **covalent bond** that holds the atoms together. Because forces cannot be seen, we represent only the presence of the shared electron pair between the atoms (by a pair of dots or a line) and remember that an attractive force is also there.

covalent bond The attractive force that results between two atoms that are both attracted to a shared pair of electrons.

FIGURE 4.9 Orbital overlap during covalent bond formation.



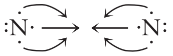
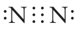
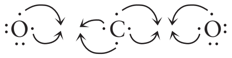
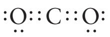
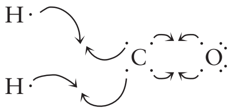
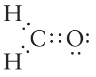
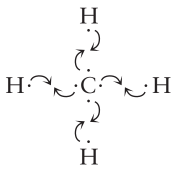
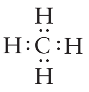
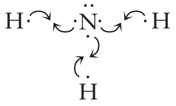
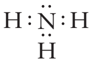
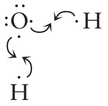
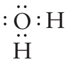
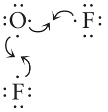
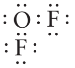
a Separated atoms **b** Orbitals touch **c** Orbitals overlap; a covalent bond is formed

Covalent bonding between like atoms has been described, but it also occurs between unlike atoms. Examples of both types are given in **Table 4.3**. Lewis structures, like those in **Table 4.3**, are most easily drawn by using a systematic approach such as the one represented by the following steps:

1. Use the molecular formula to determine how many atoms of each kind are in the molecule.
2. Use the given connecting pattern of the atoms to draw an initial structure for the molecule, with the atoms arranged properly.
3. Determine the total number of valence-shell electrons contained in the atoms of the molecule.
4. Put one pair of electrons between each bonded pair of atoms in the initial structure drawn in Step 2. Subtract the number of electrons used in this step from the total number determined in Step 3. Use the remaining electrons to complete the octets of all atoms in the structure, beginning with the atoms that are present in greatest number in the molecule. Remember, hydrogen atoms require only one pair to achieve the electronic configuration of helium.
5. If all octets cannot be satisfied with the available electrons, move nonbonding pairs (those that are not between bonded atoms) to positions between bonded atoms to complete octets. This will create **double** or **triple bonds** between some atoms.

double and triple bonds The bonds resulting from the sharing of two and three pairs of electrons, respectively.

TABLE 4.3 Examples of Covalent Bonding

Molecule	Atomic Lewis Structure	Sharing Pattern	Molecular Lewis Structure
Nitrogen gas (N_2)	$\cdot\ddot{\underset{\cdot}{N}}\cdot$ ($1s^22s^22p^3$)		
Carbon dioxide (CO_2) (each O is bonded to the C)	$\cdot\dot{\underset{\cdot}{C}}\cdot$ ($1s^22s^22p^2$) $:\ddot{\underset{\cdot}{O}}\cdot$ ($1s^22s^22p^4$)		
Formaldehyde (H_2CO) (each H and the O are bonded to the C)	$\cdot\dot{\underset{\cdot}{C}}\cdot$ ($1s^22s^22p^2$) $:\ddot{\underset{\cdot}{O}}\cdot$ ($1s^22s^22p^4$) $H\cdot$ ($1s^1$)		
Methane (CH_4) (each H is bonded to the C)	$\cdot\dot{\underset{\cdot}{C}}\cdot$ ($1s^22s^22p^2$) $H\cdot$ ($1s^1$)		
Ammonia (NH_3) (each H is bonded to the N)	$\cdot\ddot{\underset{\cdot}{N}}\cdot$ ($1s^22s^22p^3$) $H\cdot$ ($1s^1$)		
Water (H_2O) (each H is bonded to the O)	$:\ddot{\underset{\cdot}{O}}\cdot$ ($1s^22s^22p^4$) $H\cdot$ ($1s^1$)		
Oxygen difluoride (OF_2) (each F is bonded to the O)	$:\ddot{\underset{\cdot}{O}}\cdot$ ($1s^22s^22p^4$) $:\dot{\underset{..}{F}}:$ ($1s^22s^22p^5$)		

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 4.11 Drawing Lewis Structures

Ammonia (NH_3) is a gaseous compound with a sharp, pungent odor. Aromatic ammonia spirit is used in medicine to treat fainting as this substance is passed quickly under the nose.

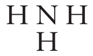
Draw Lewis structures for the following molecules:

a. NH_3 **b.** SO_3 **c.** C_2H_2

Solution a.

STEP 1: The formula indicates that the molecule contains one nitrogen (N) atom and three hydrogen (H) atoms.

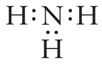
STEP 2: The connecting pattern will have to be given to you in some form. **Table 4.3** shows that each H atom is connected to the N atom; thus, we draw



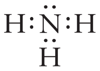
$$\begin{array}{ccc} H & N & H \\ & H & \end{array}$$

STEP 3: Nitrogen is in group VA(15) of the periodic table and so has five valence electrons; hydrogen is in group IA(1) and has one valence electron. The total is eight (five from one N atom and three from the three H atoms).

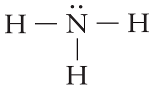
STEP 4: We put one pair of electrons between each H atom and the N atom in the initial structure drawn in Step 2:



This required six of the eight available electrons. The remaining pair is used to complete the octet of nitrogen. Remember, hydrogen achieves the noble gas configuration of helium with only two electrons:



or

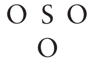


STEP 5: All octets are satisfied by Step 4, so nothing more needs to be done.

Solution b.

STEP 1: The formula indicates that one sulfur (S) and three oxygen (O) atoms are present in a molecule.

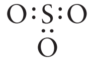
STEP 2: Each O atom is bonded only to the S atom; thus, we draw



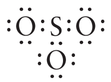
$$\begin{array}{ccc} O & S & O \\ & O & \end{array}$$

STEP 3: Sulfur and oxygen are both in group VIA(16), and so each atom has 6 valence electrons. The total is 24 (6 from the one S atom and 18 from the three O atoms).

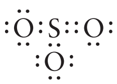
STEP 4: We put one pair of electrons between each O atom and the S atom:



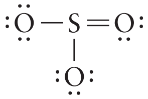
This required 6 of the 24 available electrons. The remaining 18 are used to complete the octets, beginning with the O atoms:



STEP 5: We see that the octet of sulfur is not completed, even though all available electrons have been used. If one nonbonding pair of any one of the three O atoms is moved to a bonding position between the oxygen and sulfur, it will help satisfy the octet of both atoms. The final Lewis structure is given below. Note that it contains a double bond between one of the oxygens and the sulfur:

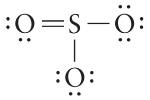


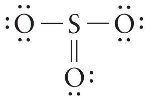
or



Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

If a nonbonding pair of electrons from either of the other two oxygens is used, the following structures result. These are just as acceptable as the preceding structures:





Solution c.

STEP 1: The formula indicates two carbon (C) atoms and two hydrogen (H) atoms per C_2H_2 molecule.

STEP 2: The C atoms are bonded to each other, and one H atom is bonded to each C atom.

$$\mathrm{H\ C\ C\ H}$$

STEP 3: Carbon is in group IVA(14) and has four valence electrons; hydrogen is in group IA(1) and has one valence electron. The total electrons available is ten (eight from the two C atoms and two from the two H atoms).

STEP 4: We put one pair of electrons between the two C atoms and between each C atom and H atom.

$$\mathrm{H{:}C{:}C{:}H}$$

This required six of the available ten electrons. The remaining four electrons are used to complete the C octets (remember, hydrogen needs only two electrons):

$$\mathrm{H{:}C{:}\underset{\cdot\cdot}{\overset{\cdot\cdot}{C}}{:}H}$$

STEP 5: All electrons are used in Step 4, but the octet of one C atom is still incomplete. It needs two more pairs. If both nonbonding pairs on the second C atom were shared with the first C atom, both carbons would have complete octets. The result is

$$\mathrm{H{:}C{:}{:}{:}C{:}H} \qquad \text{or} \qquad \mathrm{H{-}C{\equiv}C{-}H}$$

This molecule contains a triple bond (three shared pairs) between the C atoms.

✔ **LEARNING CHECK 4.11** Draw Lewis structures for the following molecules:

a. CH_4 (each H atom is bonded to the C atom)
b. H_2CO (the O atom and two H atoms are each bonded to the C atom)
c. HNO_3 (the O atoms are each bonded to the N atom, and the H atom is bonded to one of the O atoms)

4.7 Polyatomic Ions

Learning Objective 7 Draw correct Lewis structures for polyatomic ions.

An interesting combination of ionic and covalent bonding is found in compounds that contain **polyatomic ions**. These ions are covalently bonded groups of atoms that carry a net electrical charge. With the exception of the ammonium ion, NH_4^+, the common polyatomic ions are negatively charged.

polyatomic ions Covalently bonded groups of atoms that carry a net electrical charge.

Lewis structures can be drawn for polyatomic ions with just a slight modification in the steps given earlier for covalently bonded molecules. In Step 3, the total number of electrons available is obtained by first determining the total number of valence-shell electrons contained in the atoms of the ion. To this number are added electrons representing the number required to give the negative charge to the ion.

For example, in the SO_4^{2-} ion, the total number of valence-shell electrons is thirty, with six coming from the sulfur atom and six from each of the four oxygen atoms. To this number we add two, because two additional electrons are required to give the group of neutral atoms the charge of 2− found on the ion. This gives thirty-two total available electrons.

The only exception to this procedure for the common polyatomic ions is for the positively charged ammonium ion, NH_4^+. In this case, the number of electrons available is the total number of valence electrons minus one, because one electron would have to be removed from the neutral group of atoms to produce the + charge on the ion.

Example 4.12 Lewis Structures for Polyatomic Ions

Sulfate ions (SO_4^{2-}) in combination with zinc (zinc sulfate) is used medically as a dietary supplement for treating zinc deficiency.

Draw Lewis structures for the following polyatomic ions. The connecting patterns of the atoms to each other are indicated.

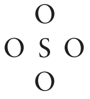
a. SO_4^{2-} (each O atom is bonded to the S atom)
b. NO_3^- (each O atom is bonded to the N atom)
c. $H_2PO_4^-$ (each O atom is bonded to the P atom, and each H atom is bonded to an O atom)

Solution a.

The only difference between drawing Lewis structures for molecules and polyatomic ions comes in Step 3, where the total number of valence-shell electrons is determined.

STEP 1: The formula indicates the ion contains one sulfur (S) atom and four oxygen (O) atoms.

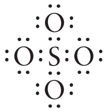
STEP 2: The given bonding relationships lead to the following initial structure:



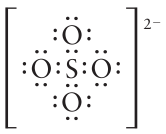
$$\begin{array}{ccc} & \mathrm{O} & \\ \mathrm{O} & \mathrm{S} & \mathrm{O} \\ & \mathrm{O} & \end{array}$$

STEP 3: Both the S and O atoms are in group VIA(16), so each atom contributes six valence electrons. The total number of valence-shell electrons from the atoms is therefore 5 × 6 = 30. However, the ion has a 2− charge. This charge comes from the presence of two electrons in the ion in addition to the electrons from the constituent atoms. These two additional electrons must be included in the total valence-shell electrons. Thus, the total number of electrons is 30 + 2 = 32.

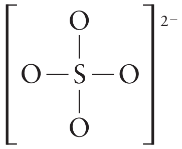
STEP 4: The following is obtained when the 32 electrons are distributed among the atoms of the initial structure of Step 2:



STEP 5: All octets are satisfied by Step 4. However, it is conventional to enclose Lewis structures of polyatomic ions in brackets and to indicate the net charge on the ion. Thus, the Lewis structures are



or

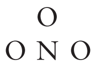


where the second structure does not show nonbonding (unshared) electron pairs, and the bonding pairs are represented by lines.

Solution b.

STEP 1: Three oxygen (O) atoms and one nitrogen (N) atom are found in the ion.

STEP 2:

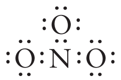


$$\begin{array}{ccc} & \mathrm{O} & \\ \mathrm{O} & \mathrm{N} & \mathrm{O} \end{array}$$

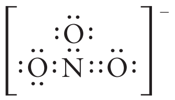
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STEP 3: Electrons from oxygen = 3 × 6 = 18.
Electrons from nitrogen = 1 × 5 = 5.
One electron comes from the ionic charge = 1.
Total electrons = 18 + 5 + 1 = 24.

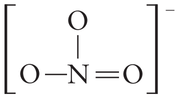
STEP 4:



STEP 5: The octet of nitrogen is not satisfied by Step 4, so an unshared pair of electrons on an O atom must be shared with the N atom. This will form a double bond in the ion. The resulting Lewis structures are



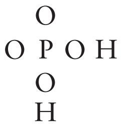
or



Solution c.

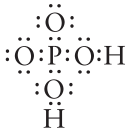
STEP 1: Two hydrogen (H) atoms, one phosphorus (P) atom, and four oxygen (O) atoms are found in the ion.

STEP 2:

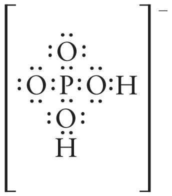


STEP 3: Electrons from hydrogen = 2 × 1 = 2.
Electrons from oxygen = 4 × 6 = 24.
Electrons from phosphorus = 1 × 5 = 5.
Electron from ionic charge = 1.
Total electrons = 2 + 24 + 5 + 1 = 32.

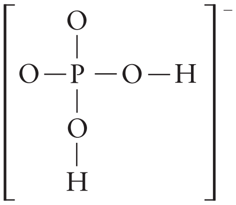
STEP 4:



STEP 5: All octets are satisfied by Step 4 (remember, H atoms are satisfied by a single pair of electrons). The resulting Lewis structures are



or



✔ **LEARNING CHECK 4.12** Draw Lewis structures for the following polyatomic ions:

a. PO_4^{3-} (each O atom is bonded to the P atom)
b. SO_3^{2-} (each O atom is bonded to the S atom)
c. NH_4^{+} (each H atom is bonded to the N atom)

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

narikan/Shutterstock.com

FIGURE 4.10 Up to 60% of the adult human body is water. The bent (rather than linear) shape of water molecules gives rise to properties that support life.

4.8 Shapes of Molecules and Polyatomic Ions

Learning Objective 8 Use VSEPR theory to predict the shapes of molecules and polyatomic ions.

Most molecules and polyatomic ions do not have flat, two-dimensional shapes like those implied by the molecular Lewis structures of **Table 4.3**. In fact, the atoms of most molecules and polyatomic ions form distinct three-dimensional shapes. Being able to predict the shape is important because the shape contributes to the properties of the molecule or ion (see **Figure 4.10**). This can be done quite readily for molecules composed of representative elements.

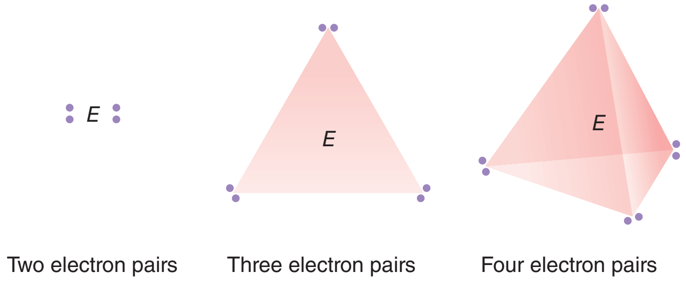
To predict molecular or ionic shapes, first draw Lewis structures for the molecules or ions using the methods discussed in **Sections 4.6** and **4.7**. Once you have drawn the Lewis structure for a molecule or ion, you can predict its shape by applying a simple theory to the structure. The theory is called the *valence-shell electron-pair repulsion theory*, or **VSEPR theory** (sometimes pronounced "vesper" theory). According to VSEPR theory, electron pairs in the valence shell of an atom are repelled by other electron pairs and get as far away from one another as possible. Any atom in a molecule or ion that is bonded to two or more other atoms is called a *central atom*. When the VSEPR theory is applied to the valence-shell electrons of central atoms, the shape of the molecule or ion containing the atoms can be predicted. Two rules are followed:

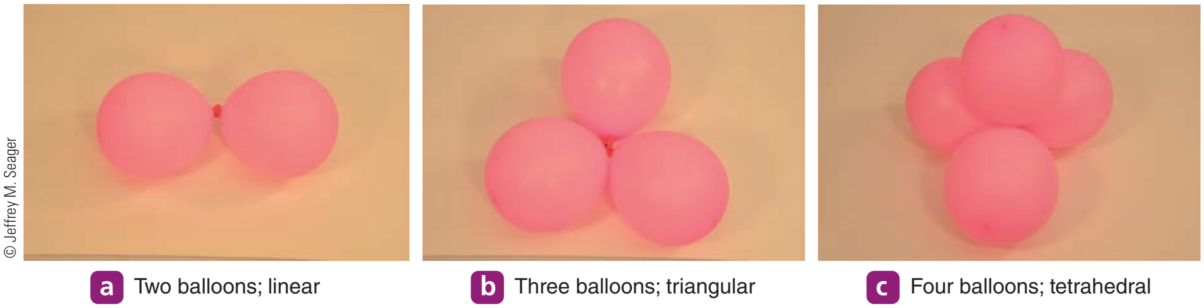
VSEPR theory A theory based on the mutual repulsion of electron pairs. It is used to predict molecular shapes.

1. All valence-shell electron pairs around the central atom are counted equally, regardless of whether they are bonding or nonbonding pairs.
2. Double or triple bonds between atoms are treated like a single pair of electrons when predicting shapes.

The electron pairs around a central atom will orient themselves in space to get as far away from one another as possible. Thus, two pairs will be oriented with one pair on each opposite side of the central atom. Three pairs will form a triangle around the central atom, and four pairs will be located at the corners of a regular tetrahedron with the central atom in the center (see **Figures 4.11** and **4.12**). The VSEPR theory can be used to predict shapes of molecules and ions with five or more pairs on the central atom, but we will not go beyond four pairs in this book.

FIGURE 4.11 Arrangements of electron pairs around a central atom (E).




© Jeffrey M. Seager

a Two balloons; linear **b** Three balloons; triangular **c** Four balloons; tetrahedral

FIGURE 4.12 When balloons of the same size and shape are tied together, they will assume positions like those taken by pairs of valence electrons around a central atom. Where would the central atom be located in these balloon models?

Example 4.13 Applications of VSEPR Theory

Carbon dioxide (CO_2) is commonly used as an insufflation gas for minimally invasive surgery (such as laparoscopy) to enlarge body cavities to provide better visibility of the surgical area.

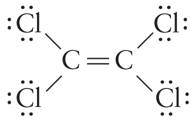
Draw Lewis structures for the following molecules, apply the VSEPR theory, and predict the shape of each molecule:

a. CO_2 (each O atom is bonded to the C atom)
b. C_2Cl_4 (the C atoms are bonded together, and two Cl atoms are bonded to each C atom)
c. NH_3 (each H atom is bonded to the N atom)
d. H_2O (each H atom is bonded to the O atom)

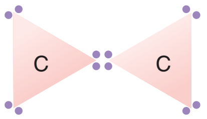
Solution

a. The Lewis structure is $:\ddot{O}=C=\ddot{O}:$. The central atom is carbon (C) and it has two pairs of electrons in the valence shell surrounding it (remember, each double bond is treated like a single pair of electrons in the VSEPR theory). The two pairs will be located on opposite sides of the C atom, so the molecule has the shape drawn above with the O, C, and O atoms in a line; it is a linear molecule.

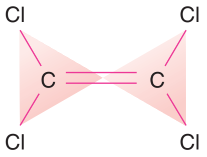
b. The Lewis structure is



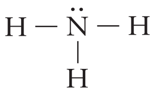
Both C atoms are central atoms in this molecule, and each one has three electron pairs in the valence shell (again, the double bond is treated as only one pair). The three pairs around each C atom will be arranged in the shape of a triangle:



Thus, the molecule has the shape of two flat triangles in the same plane connected together at one point:

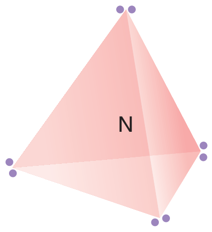


c. The Lewis structure is

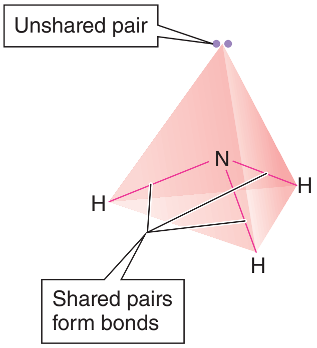


$$\begin{array}{c}H-\ddot{N}-H\\ |\\ H\end{array}$$

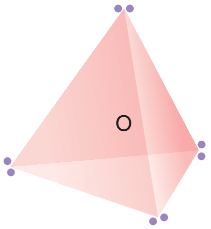
The central atom is nitrogen (N), and it has four electron pairs in the valence shell. The four pairs will be located at the corners of a tetrahedron with the N atom in the middle:



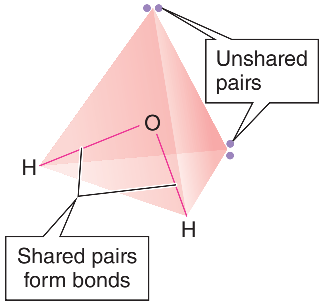
The shape of the molecule is determined only by the positions of the atoms, not by the position of the unshared pair of electrons. Thus, the NH_3 molecule has the shape of a pyramid with a triangular base. The N atom is at the peak of the pyramid, and an H atom is at each corner of the base:



d. The Lewis structure is $\mathrm{H}:\ddot{\underset{\cdot\cdot}{\mathrm{O}}}:\mathrm{H}$. The central atom is oxygen (O), and it is seen to have four pairs of electrons in its valence shell. The four pairs will be located at the corners of a tetrahedron with the O atom in the middle:

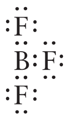


Once again, the shape of the molecule is determined by the locations of the atoms. Thus, H_2O is seen as having a bent or angular shape:



✔ **LEARNING CHECK 4.13** Predict the shapes of the following molecules by applying the VSEPR theory:

a. BF_3 (the Lewis structure is



$$\begin{array}{l} :\ddot{\underset{\cdot\cdot}{\mathrm{F}}}: \\ \;\;\mathrm{B}:\ddot{\underset{\cdot\cdot}{\mathrm{F}}}: \\ :\ddot{\underset{\cdot\cdot}{\mathrm{F}}}: \end{array}$$

for this molecule, which does not obey the octet rule).

b. CCl_4 (each Cl atom is bonded to the C atom)

c. SO_2 (each O atom is bonded to the S atom)

d. CS_2 (each S atom is bonded to the C atom)

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 4.14 More Applications of VSEPR Theory

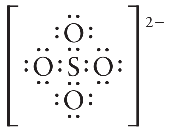
Nitrates (NO_3^-) are vasodilators, helping to widen blood vessels. Nitrates can be used to treat angina (chest pain).

Use the VSEPR theory to predict the shapes of the following polyatomic ions. The Lewis structures were drawn in Example 4.12.

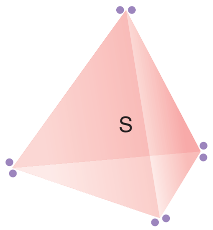
a. SO_4^{2-}
b. NO_3^-

Solution

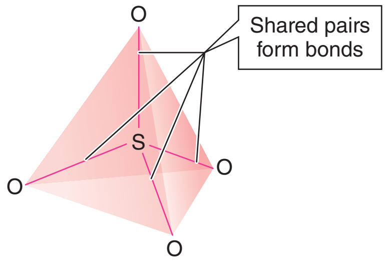
a. The Lewis structure from Example 4.12 is



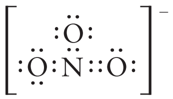
We see that sulfur is the central atom, and it has four electron pairs around it. The four pairs will be located at the corners of a tetrahedron with the S in the middle.



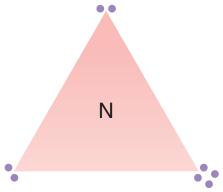
The shape of the ion is determined by the location of the oxygen atoms. Thus, the ion has a tetrahedral shape:



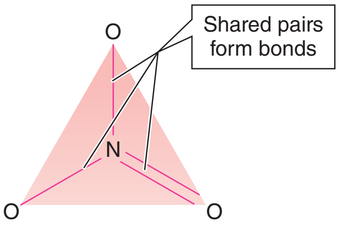
b. The Lewis structure from Example 4.12 is



We see that nitrogen is the central atom, and it has three electron pairs around it. Remember, the double bond formed by the two shared electron pairs between the nitrogen and one of the oxygens counts as only one pair in the VSEPR theory. The three pairs will form a triangle around the N.



An oxygen is located at each corner of the triangle, so the ion has a flat triangular shape:



✔ **LEARNING CHECK 4.14** Use the VSEPR theory to predict the shapes of the following polyatomic ions. The Lewis structures were drawn in Learning Check 4.12.

a. PO_4^{3-} b. SO_3^{2-} c. NH_4^+

4.9 The Polarity of Covalent Molecules

Learning Objective 9 Use electronegativities to classify covalent bonds of molecules, and determine whether covalent molecules are polar or nonpolar.

nonpolar covalent bond A covalent bond in which the bonding pair of electrons is shared equally by the bonded atoms.

electronegativity The tendency of an atom to attract shared electrons of a covalent bond.

bond polarization A result of shared electrons being attracted to the more electronegative atom of a bonded pair of atoms.

polar covalent bond A covalent bond that shows bond polarization; that is, the bonding electrons are shared unequally.

Molecules of chlorine (Cl—Cl) and hydrogen chloride (H—Cl) have a number of similarities. For example, they contain two atoms each and are therefore diatomic molecules, and the atoms are held together by a single covalent bond. Some differences also exist, the most obvious being the homoatomic nature of the chlorine molecule (an element) and the heteroatomic nature of the hydrogen chloride molecule (a compound). This difference influences the distribution of the shared electrons in the two molecules.

An electron pair shared by two identical atoms is attracted equally to each of the atoms, and the probability of finding the electrons close to an atom is equal for the two atoms. Thus, on average, the electrons spend exactly the same amount of time associated with each atom. Covalent bonds of this type are called **nonpolar covalent bonds**.

Different atoms generally have different tendencies to attract the shared electrons of a covalent bond. A measurement of this tendency is called **electronegativity**. The electronegativity of the elements is a property that follows trends in the periodic table. It increases from left to right across a period and decreases from top to bottom of a group. These trends are shown in **Table 4.4**, which contains electronegativity values for the common representative elements. As a result of electronegativity differences, the bonding electrons shared by two different atoms are shared unequally. The electrons spend more of their time near the atom with the higher electronegativity. The resulting shift in average location of bonding electrons is called **bond polarization** and produces a **polar covalent bond**.

TABLE 4.4 Electronegativities for the Common Representative Elements

Increasing electronegativity →

		H 2.1					
Li 1.0	Be 1.5		B 2.0	C 2.5	N 3.0	O 3.5	F 4.0
Na 0.9	Mg 1.2		Al 1.5	Si 1.8	P 2.1	S 2.5	Cl 3.0
K 0.8	Ca 1.0		Ga 1.6	Ge 1.8	As 2.0	Se 2.4	Br 2.8
Rb 0.8	Sr 1.0		In 1.7	Sn 1.8	Sb 1.9	Te 2.1	I 2.5
Cs 0.7	Ba 0.9						

↓ *Decreasing electronegativity*

HEALTH CONNECTIONS **4.2**

Are All Iron Preparations Created Equal?

The short answer to the above question is no. Neither are the people who take them—at least in terms of their ability to absorb the iron. Of all the elements in the body, iron is one of the most important. It is so important that the body has developed several mechanisms for transporting and storing it. One of the most important functions of iron is its role as part of the hemoglobin molecule in transporting oxygen to the body cells and exchanging other gases.

There are numerous causes of iron deficiency anemia that require patients to take an iron supplement. Among these causes are blood loss from injury, ulcers, absorption problems, pregnancy, rapid growth demands, menstruation, etc. If it is determined by a health professional that a patient needs to take supplemental iron orally, what form should be used?

There are several different forms available "over the counter," and they are all labeled "iron." In most over-the-counter products, the iron is in the ferrous or 2+ ionic form. The other part of the over-the-counter products will typically be sulfate, gluconate, or fumarate. Which product you choose will determine how much iron you are getting per dosage for your money. Ferrous sulfate contains only about 20% iron, ferrous gluconate only about 12% iron, and ferrous fumarate about 33% iron. You should also check with your health professional to make certain that you are not overdosing.

MICROELEMENT
IRON (Fe)

Designer491/Shutterstock.com

Iron preparations vary in the amount of iron present.

As a result of the unequal electron sharing, the more electronegative atom acquires a partial negative charge ($\delta-$), and the less electronegative atom has a partial positive charge ($\delta+$). The molecule as a whole has no net charge, just an uneven charge distribution.

Example 4.15 The Periodic Table and Properties

Use only the periodic table to determine the following for the diatomic covalent molecules listed below: (1) the more electronegative element, (2) the direction of bond polarization, and (3) the charge distribution resulting from the polarization.

a. I—Cl b. Br—Br c. C≡O

Carbon monoxide (CO) is harmful when breathed because it displaces oxygen in the blood, depriving the heart, brain, and other vital organs of oxygen.

Solution

a. Both chlorine (Cl) and iodine (I) belong to group VIIA(17); chlorine is higher in the group and therefore is the more electronegative. The bond polarization (shift in average bonding-electron location) will be towards chlorine, as indicated by the arrow shown below the bond. The result is a partial negative charge on Cl and a partial positive charge on I:

$$\overset{\delta+}{\mathrm{I}}\underset{\rightarrow}{-}\overset{\delta-}{\mathrm{Cl}}$$

b. Since both bromine (Br) atoms have the same electronegativity, no bond polarization or unequal charge distribution results. The molecule is nonpolar covalent and is represented as Br—Br.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

c. Oxygen (O) and carbon (C) both belong to the second period. Oxygen, being located farther to the right in the period, is the more electronegative. Thus, the molecule is represented as

$$\overset{\delta+}{\mathrm{C}}\underset{\rightarrow}{\equiv}\overset{\delta-}{\mathrm{O}}$$

✔ LEARNING CHECK 4.15 Use only the periodic table and show the direction of any bond polarization and resulting charge distribution in the following molecules:

a. N≡N b. I—Br c. H—Br

The extent of bond polarization depends on electronegativity differences between the bonded atoms and forms one basis for a classification of bonds. When the electronegativity difference (ΔEN) between the bonded atoms is 0.0, the bond is classified as nonpolar covalent (the electrons are shared equally). When ΔEN is 2.1 or greater, the bond is classified as ionic (the electrons are transferred). When ΔEN is between 0.0 and 2.1, the bond is classified as polar covalent (the electrons are unequally shared, and the bond is polarized). Note, however, that the change from purely covalent to completely ionic compounds is gradual and continuous as ΔEN values change. Thus, a bond between hydrogen (H) and boron (B) ($\Delta EN = 0.1$) is classified as polar, but the electron sharing is only slightly unequal and the bond is only slightly polar (see **Figure 4.13**). As the values in **Table 4.4** indicate, compounds formed by a reaction of a metal with a nonmetal are generally ionic, while those between nonmetals are either nonpolar or polar covalent.

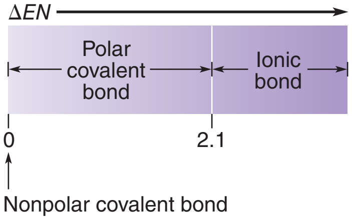


FIGURE 4.13 The darker the shading, the larger ΔEN is for the bonded atoms. Larger ΔEN values correspond to greater inequality in the sharing of the bonding electrons.

Example 4.16 Classifying Covalent Bonds

Using **Table 4.4**, classify the bonds in the following compounds as nonpolar covalent, ionic, or polar covalent:

a. ClF b. MgO c. PI_3

Magnesium oxide (MgO) is used in some antacids and in some laxatives.

Solution

a. The electronegativities of chlorine (Cl) and fluorine (F) are 3.0 and 4.0, respectively. Obtain the ΔEN value by subtracting the smaller from the larger, regardless of the order of the elements in the formula. Thus,

$$\Delta EN = 4.0 - 3.0 = 1.0$$

and the bond is polar covalent.

b. Similarly,

$$\Delta EN = 3.5 - 1.2 = 2.3$$

and the bond is ionic.

c. The ΔEN is determined for each phosphorus−iodine bond:

$$\Delta EN = 2.5 - 2.1 = 0.4$$

Thus, each bond is classified as polar covalent.

✔ LEARNING CHECK 4.16 Using Table 4.4, classify the bonds in the following compounds as nonpolar covalent, ionic, or polar covalent:

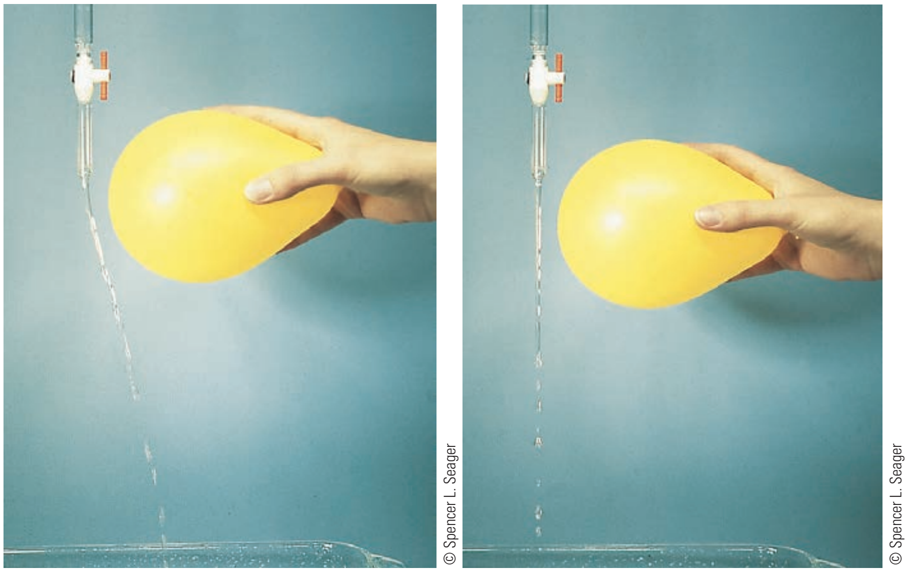
a. KF b. NO c. AlN d. K_2O

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

You can now predict the polarity of bonds within molecules, but it is also important to be able to predict the polar nature of the molecules themselves. The terms *polar* and *nonpolar*, when used to describe molecules, indicate their electrical charge symmetry (see **Figure 4.14**). In **polar molecules** (often called dipoles), the charge distribution resulting from bond polarizations is nonsymmetric. In **nonpolar molecules**, any charges caused by bond polarization are symmetrically distributed through the molecule. **Table 4.5** illustrates polar and nonpolar molecules. The molecular shapes were determined by using the VSEPR theory.

polar molecule A molecule that contains polarized bonds and in which the resulting charges are distributed nonsymmetrically throughout the molecule.

nonpolar molecule A molecule that contains no polarized bonds, or a molecule containing polarized bonds in which the resulting charges are distributed symmetrically throughout the molecule.


© Spencer L. Seager

© Spencer L. Seager

a A stream of polar water molecules is attracted by a charged balloon.

b A stream of nonpolar carbon tetrachloride (CCl_4) molecules is not affected by a charged balloon.

FIGURE 4.14 Polar and nonpolar molecules are affected differently by electrical charges. The ΔEN between C and Cl is 0.5. Propose a reason why CCl_4 molecules are nonpolar.

TABLE 4.5 The Polarity of Molecules

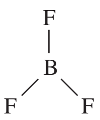
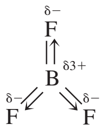
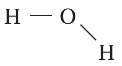
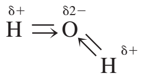
Molecular Formula	Geometric Structure	Bond Polarization and Molecular Charge Distribution	Geometry of Charge Distribution	Classification of Charge Distribution	Classification of Molecule
H_2	H — H	H — H	No charges	No charges	Nonpolar
HCl	H — Cl	$\overset{\delta+}{\mathrm{H}} \Rightarrow \overset{\delta-}{\mathrm{Cl}}$	+ −	Nonsymmetric	Polar
CO_2	O = C = O	$\overset{\delta-}{\mathrm{O}} \Lleftarrow \overset{\delta 2+}{\mathrm{C}} \Rrightarrow \overset{\delta-}{\mathrm{O}}$	− 2+ −	Symmetric	Nonpolar
BF_3			− 3+ − −	Symmetric	Nonpolar
N_2O	N ≡ N — O	$\mathrm{N} \equiv \overset{\delta+}{\mathrm{N}} \Rightarrow \overset{\delta-}{\mathrm{O}}$	+ −	Nonsymmetric	Polar
H_2O			+ 2− +	Nonsymmetric	Polar

TABLE 4.6 Greek Numerical Prefixes

Number	Prefix
1	*mono-*
2	*di-*
3	*tri-*
4	*tetra-*
5	*penta-*
6	*hexa-*
7	*hepta-*
8	*octa-*
9	*nona-*
10	*deca-*

4.10 More about Naming Compounds

Learning Objective 10 Write correct formulas for ionic compounds containing representative metals and polyatomic ions, and correctly name binary covalent compounds and compounds containing polyatomic ions.

In **Section 4.4**, we discussed the rules for naming binary ionic compounds. In this section, we expand the rules to include the naming of binary covalent compounds and ionic compounds that contain polyatomic ions.

It is apparent from **Table 4.4** that covalent bonds (including polar covalent) form most often between representative elements classified as nonmetals. It is not possible to predict formulas for these compounds in a simple way, as was done for ionic compounds in **Section 4.4**. However, simple rules do exist for naming binary covalent compounds on the basis of their formulas. The rules are similar to those used to name binary ionic compounds: (1) Give the name of the less electronegative element first (the element given first in the formula), (2) give the stem of the name of the more electronegative element next and add the suffix *-ide,* and (3) indicate the number of each type of atom in the molecule by means of the Greek prefixes listed in **Table 4.6**.

Example 4.17 Naming Binary Covalent Compounds

Name the following binary covalent compounds:

a. CO_2 b. CO c. NO_2 d. N_2O_5 e. CS_2

Solution

a. The elements are carbon (C) and oxygen (O), and carbon is the less electronegative. Because the stem of oxygen is *ox-,* the two portions of the name will be carbon and oxide. Only one C atom is found in the molecule, but the prefix *mono-* is not used when it appears at the beginning of a name. The two O atoms in the molecule are indicated by the prefix *di-*. The name therefore is carbon dioxide.
b. Similarly, we arrive at the name carbon monoxide for CO.
c. NO_2 is assigned the name nitrogen dioxide.
d. N_2O_5 is assigned the name dinitrogen pentoxide. *Note*: The a is dropped from the *penta-* prefix for oxygen; this is done to avoid the pronunciation problem created by having two vowels next to each other in a name (dinitrogen pentaoxide).
e. CS_2 is named carbon disulfide.

✔ **LEARNING CHECK 4.17** Name the following binary covalent compounds:

a. SO_3 b. BF_3 c. S_2O_7 d. CCl_4

The formulas and names of some common polyatomic ions are given in **Table 4.7**. From this information, the formulas and names for compounds containing polyatomic ions can be written. The rules are essentially the same as those used earlier for binary ionic compounds. In the formulas, the metal (or ammonium ion) is written first, the positive and negative charges must add up to zero, and parentheses are used around the polyatomic ions if more than one is used. In names, the positive metal (or ammonium) ion is given first, followed by the name of the negative polyatomic ion (see **Figure 4.15**). No numerical prefixes are used except where they are a part of the polyatomic ion name. Names and formulas of acids (compounds in which hydrogen is bound to polyatomic ions) will be given in Chapter 9.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STUDY TOOLS 4.1

Help with Polar and Nonpolar Molecules

When concepts are closely related, it is very easy to become confused. In this chapter, the terms *polar* and *nonpolar* are used to describe both bonds and molecules. What is the correct way to apply the terms?

It may be helpful to remember the numbers 3 and 2: three types of bonds, but only two types of molecules. The bonds are nonpolar covalent ($\Delta EN = 0$), polar covalent ($\Delta EN = 0.1-2.0$), and ionic ($\Delta EN = 2.1$ or greater). Remember that compounds bonded by ionic bonds do not form molecules, so there are only two types of molecules: nonpolar and polar.

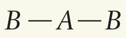
The polarity of a molecule depends on two factors: (1) the polarity of the bonds between the atoms of the molecule, and (2) the geometric arrangement of the atoms in space. First, determine whether any of the bonds between atoms are polar. If only nonpolar bonds are present, the molecule will be nonpolar regardless of the geometric arrangement of the atoms. However, if one or more polar bonds are found, the arrangement of the atoms must be considered as a second step.

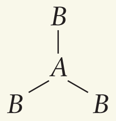
For diatomic (two-atom) molecules, a polar bond between the atoms results in a polar molecule:

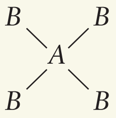
$A—A$ $\Delta EN = 0$ because atoms are identical; nonpolar
$A—B$ If $\Delta EN = 0$; nonpolar
$A—B$ If $\Delta EN = 0.1-2.0$; polar

Thus, we see that for diatomic molecules, the type of bond between atoms and the resulting type of molecule is the same.

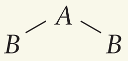
For a molecule that contains polar bonds and three or more atoms, the molecular geometry must be known and taken into account before the polar nature of the molecule can be determined. Remember, the unequal sharing of electrons between two atoms bonded by a polar bond will cause one of the bonded atoms to have a partial positive charge and one a partial negative charge. If these atoms with their charges are symmetrically arranged in space to form the molecule, the molecule will be nonpolar. Thus, each of the following planar (flat) molecules will be nonpolar even if the bonds between the atoms are polar:

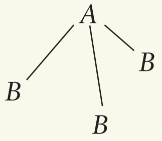






On the other hand, each of the following molecules will be polar if they contain polar bonds, because the resulting charges on the atoms are not distributed symmetrically in space:





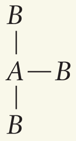
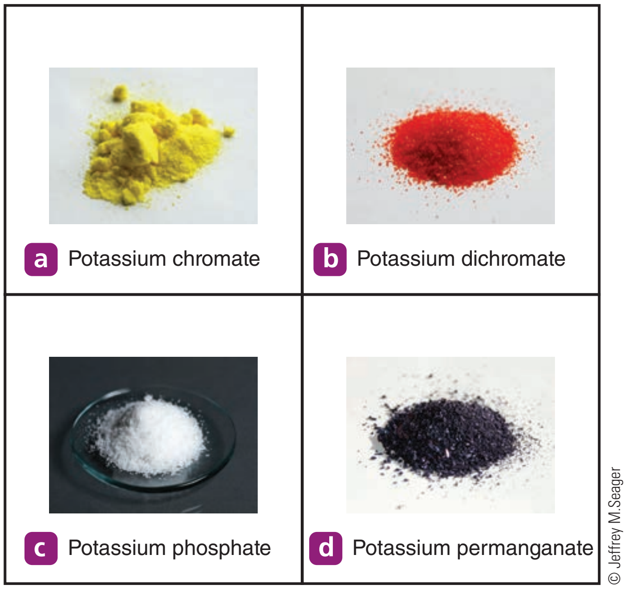


TABLE 4.7 Some Common Polyatomic Ions

Very Common		Common	
NH_4^+	ammonium	CrO_4^{2-}	chromate
$C_2H_3O_2^-$	acetate	$Cr_2O_7^{2-}$	dichromate
CO_3^{2-}	carbonate	NO_2^-	nitrite
ClO_3^-	chlorate	MnO_4^-	permanganate
CN^-	cyanide	SO_3^{2-}	sulfite
HCO_3^-	hydrogen carbonate (bicarbonate)	ClO^-	hypochlorite
OH^-	hydroxide	HPO_4^{2-}	hydrogen phosphate
NO_3^-	nitrate	$H_2PO_4^-$	dihydrogen phosphate
PO_4^{3-}	phosphate	HSO_4^-	hydrogen sulfate (bisulfate)
SO_4^{2-}	sulfate	HSO_3^-	hydrogen sulfite (bisulfite)

FIGURE 4.15 Examples of potassium compounds that contain polyatomic ions, resulting in strikingly different colors. The samples are shown as solids. Referring to Table 4.7, write formulas for these compounds: (a) potassium chromate, (b) potassium dichromate, (c) potassium phosphate, (d) potassium permanganate.



© Jeffrey M.Seager

Example 4.18 Writing Compound Formulas and Names

Ammonium ions (NH_4^+) are a waste product of the metabolism of animals. Fish excrete it directly into water, while in mammals it is converted into less toxic urea.

Write formulas and names for compounds composed of ions of the following metals and the polyatomic ions indicated:

a. Na and NO_3^-
b. Ca and ClO_3^-
c. K and HPO_4^{2-}
d. NH_4^+ and NO_3^-

Solution

a. Sodium (Na) is a group IA(1) metal and forms Na^+ ions. Electrical neutrality requires a combining ratio of one Na^+ for one NO_3^-. The formula is $NaNO_3$. The name is given by the metal name plus the polyatomic ion name: sodium nitrate.

b. Calcium (Ca), a group IIA(2) metal, forms Ca^{2+} ions. Electrical neutrality therefore requires a combining ratio of one Ca^{2+} for two ClO_3^- ions. The formula is $Ca(ClO_3)_2$. (*Note:* The use of parentheses around the polyatomic ion prevents the confusion resulting from writing $CaClO_{32}$, which implies that there are 32 oxygen atoms in the formula. Parentheses are always used when multiples of a specific polyatomic ion are used in a formula and are indicated by a subscript.) The name is calcium chlorate.

c. Potassium (K), a group IA(1) metal, forms K^+ ions. The required combining ratio of 2:1 gives the formula K_2HPO_4. The name is potassium hydrogen phosphate.

d. The NH_4^+ is not a metallic ion, but it behaves like one in numerous compounds. The 1:1 combining ratio gives the formula NH_4NO_3. (*Note:* The polyatomic ions are written separately, and the nitrogen atoms are not grouped to give a formula such as $N_2H_4O_3$.) The name is ammonium nitrate.

✔ **LEARNING CHECK 4.18** Write formulas and names for compounds containing ions of the following metals and the polyatomic ions indicated:

a. Ca and HPO_4^{2-}
b. Mg and PO_4^{3-}
c. K and MnO_4^-
d. NH_4^+ and $Cr_2O_7^{2-}$

4.11 Other Interparticle Forces

Learning Objective 11 Relate melting and boiling points of pure substances to the strength and type of interparticle forces present in the substances.

Ionic and covalent bonding can account for certain properties of many substances. However, some experimental observations can be explained only by proposing the existence of other types of forces between particles.

Earlier in this chapter, a crystal lattice was described in connection with ionic bonding (see **Figure 4.7**). Most pure substances (elements or compounds) in the solid state also exist in the form of a crystal lattice. However, in some of these solids, neutral atoms or molecules occupy the lattice sites instead of ions. When solids are melted, the forces holding the lattice particles in place are overcome, and the particles move about more freely in what is called the liquid state. The addition of more heat overcomes the attractive interparticle forces to a still greater extent, and the liquid is converted into a gas or vapor; the liquid boils. Particles in the vapor state move about very freely and are influenced only slightly by interparticle attractions. Thus, the temperatures at which melting and boiling take place give an indication of the strength of the interparticle forces that are being overcome. (These states of matter—solid, liquid, and gas—are discussed in more detail in Chapter 6.)

Suppose an experiment is carried out with several pure substances. Some are familiar to you, but others you probably have never seen in the solid state. The substances are listed in **Table 4.8**, together with some pertinent information.

TABLE 4.8 Some Characteristics of Selected Pure Substances

Substance	Formula or Symbol	Classification	Particles Occupying Lattice Sites
Sodium chloride	NaCl	Compound	Na^+ and Cl^- ions
Water	H_2O	Compound	H_2O molecules
Carbon monoxide	CO	Compound	CO molecules
Quartz (pure sand)	SiO_2	Compound	Si and O atoms
Copper metal	Cu	Element	Cu atoms
Oxygen	O_2	Element	O_2 molecules

The experiment is started at the very low temperature of −220°C to have all substances in the solid state. The temperature is then increased slowly and uniformly to 2600°C, at which point all the substances will be in the gaseous state. See **Table 4.9**, which gives only those temperatures corresponding to a specific change in one of the substances.

The melting points of the substances used in this experiment show that the weakest interparticle forces are found in solid oxygen. The forces then increase in the order CO, H_2O, NaCl, Cu, and SiO_2. With two exceptions, the boiling points follow the same order. How do these melting and boiling points relate to the lattice particles of these substances?

The lattice particles in solid silicon dioxide are individual atoms of silicon and oxygen. They are held together in the lattice by covalent bonds. Solids of this type are called **network solids**, and when such solids are melted or vaporized, strong covalent bonds must be broken.

network solids Solids in which the lattice sites are occupied by atoms that are covalently bonded to each other.

TABLE 4.9 The Behavior of Selected Pure Substances in Response to Heating

	Behavior or State of Substance					
Temperature (°C)	Oxygen (O_2)	Carbon Monoxide (CO)	Water (H_2O)	Salt (NaCl)	Copper (Cu)	Quartz (SiO_2)
−220	Solid	Solid	Solid	Solid	Solid	Solid
−218	**Melts**	Solid	Solid	Solid	Solid	Solid
−199	Liquid	**Melts**	Solid	Solid	Solid	Solid
−192	Liquid	**Boils**	Solid	Solid	Solid	Solid
−183	**Boils**	Gas	Solid	Solid	Solid	Solid
0	Gas	Gas	**Melts**	Solid	Solid	Solid
100	Gas	Gas	**Boils**	Solid	Solid	Solid
801	Gas	Gas	Gas	**Melts**	Solid	Solid
1083	Gas	Gas	Gas	Liquid	**Melts**	Solid
1413	Gas	Gas	Gas	**Boils**	Liquid	Solid
1610	Gas	Gas	Gas	Gas	Liquid	**Melts**
2230	Gas	Gas	Gas	Gas	Liquid	**Boils**
2595	Gas	Gas	Gas	Gas	**Boils**	Gas
2600	Gas	Gas	Gas	Gas	Gas	Gas

metallic bond An attractive force responsible for holding solid metals together. It originates from the attraction between positively charged atomic kernels that occupy the lattice sites and mobile electrons that move freely through the lattice.

The individual atoms that are the lattice particles of copper metal are held together in the lattice by what is called a **metallic bond**. As described in **Section 4.2**, the atoms of metals lose valence-shell electrons readily. Imagine a large number of metal atoms occupying lattice sites. Now imagine that the valence-shell electrons of each of the atoms move readily throughout the lattice. The attraction of the positive kernels (the metal atom nuclei plus low-level electrons) to the mobile electrons, and hence to one another, constitutes a metallic bond. The mobile electrons of the metallic bond are responsible for a number of the observed properties of metals, including high thermal conductivity, high electrical conductivity, and the characteristic metallic luster.

The bonds broken when sodium chloride (NaCl) melts or boils are ionic bonds resulting from attractions between positive (Na^+) and negative (Cl−) ions, the lattice particles in **Figure 4.7**. As shown in **Table 4.9**, these bonds are generally quite strong.

dipolar force The attractive force that exists between the positive end of one polar molecule and the negative end of another.

The lattice particles of solid carbon monoxide (CO) are the nonsymmetric CO molecules. These molecules are polar because of the nonsymmetric distribution of charges between the carbon and oxygen atoms. They are held in the solid lattice by **dipolar forces** resulting from the attraction of the positive end of one polar molecule to the negative end of another polar molecule. These forces are usually weak, and melting and vaporization take place at very low temperatures. Such substances are usually thought of as gases because that is their normal state at room temperature.

hydrogen bonding The result of attractive dipolar forces between molecules in which hydrogen atoms are covalently bonded to very electronegative elements (O, N, or F).

Water molecules, the lattice particles of ice, are also held in place by dipolar forces. However, these forces are stronger than those of the dipoles for CO. In water molecules, the hydrogens carry a partial positive charge, and the oxygen has a partial negative charge (see **Table 4.5**). Thus, the hydrogens of one molecule are attracted to the oxygens of other molecules. This attraction, called **hydrogen bonding**, is stronger than most other dipolar attractions because of the small size of the hydrogen atom and the high electronegativity of oxygen (see **Figure 4.16**). Hydrogen bonding occurs in gases, liquids, and solids composed of polar molecules in which hydrogen atoms are covalently bonded to highly electronegative elements (generally F, O, or N).

ENVIRONMENTAL CONNECTIONS 4.1

Ozone: Good Up High, Bad Nearby

Ozone, O_3, is a gas that occurs both in the Earth's upper atmosphere and at ground level. Ozone is an allotrope of oxygen. Allotropes are different molecular forms of the same element. Ozone can be good or bad for your health and the environment, depending on its location in the atmosphere.

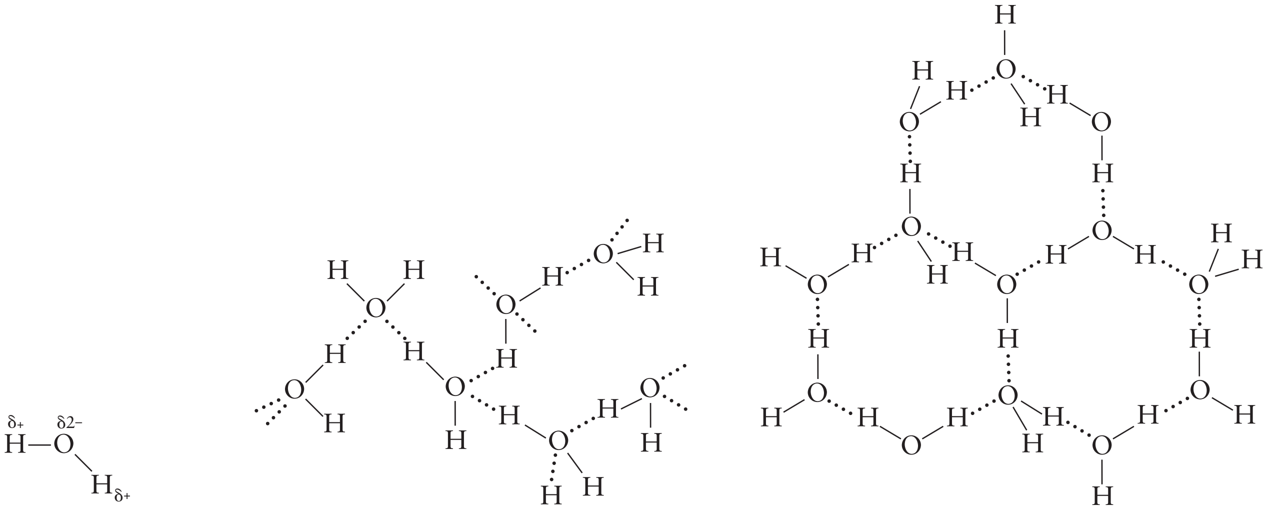
Ozone occurs in two layers of the atmosphere. The layer closest to the Earth's surface is the troposphere. Here, ground-level or "bad" ozone is an air pollutant that is harmful to breathe and damages crops, trees, and other vegetation. It is a main ingredient of urban smog. The troposphere generally extends to a level about 6 miles up from the Earth's surface. The second layer of the atmosphere, called the stratosphere, extends from the top of the troposphere to a height of about 30 miles. Ozone in the stratosphere is "good" ozone. It protects life on Earth by absorbing harmful ultraviolet (UV) radiation that is a part of sunlight.

Ozone is produced naturally in the stratosphere, but this "good" ozone is gradually being destroyed by human-produced substances referred to as ozone-depleting substances (ODS). Examples of ODS include chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons, methyl bromide, carbon tetrachloride, and methyl chloroform. These ODS materials were formerly used and sometimes are still used as air conditioner coolants, as foaming agents to make products like styrofoam, as solvents, as pesticides, and as aerosol propellants.

Even though the use of ODS compounds has been reduced or eliminated, their past use continues to influence the protective ozone layer around the earth. The good news is that research indicates that the depletion rate of the "good" ozone layer is being reduced worldwide. The changes in the protective ozone layer can be observed using satellite measurements, particularly over the polar regions of the Earth.

Hung Chung Chih/Shutterstock.com

Ozone is the main ingredient in urban smog.



(a) Polar water molecule

(b) Hydrogen bonding in liquid water

(c) Hydrogen bonding in solid water

FIGURE 4.16 Hydrogen bonding in water. Hydrogen bonds are dotted, and covalent bonds are solid.

Water is the most well-known substance in which hydrogen bonding dramatically influences the properties. These properties make water useful in many processes, including those characteristic of living organisms. Because of this widespread use, water is not often thought of as being a peculiar substance. However, it is often the peculiarities that make it so useful.

As we saw in Example 4.13d, water molecules are angular. Because of this shape and the large difference in electronegativity between hydrogen and oxygen, water molecules are polar, with partial positive charges on the hydrogens and a partial negative charge on the oxygen, as shown in **Figure 4.16(a)**. The attractions between these oppositely charged parts of the molecules result in hydrogen bonding. This is represented for the liquid and solid states of water in **Figures 4.16(b)** and **(c)**.

Let's look at some of the peculiar properties of water. As shown in **Table 4.9**, water has a normal boiling point of 100°C. This is much higher than would be predicted from the measured boiling points of compounds containing hydrogen and the other members of group VIA(16) of the periodic table. The boiling point of H_2Te is −2.2°C, of H_2Se is −41.3°C, and of H_2S is −60.3°C. Thus, it appears that the boiling point decreases with decreasing compound molecular weight. On the basis of this trend, water should boil at approximately −64°C. The 164-degree difference between predicted and measured boiling points is caused by strong hydrogen bonds between water molecules in the liquid. The other three compounds do not have strong hydrogen bonds between molecules because the electronegativites of the elements to which hydrogen is covalently bonded are too low. This deviation from prediction makes water a liquid at normal temperatures and allows it to be used in many of the ways familiar to us.

Volodymyr Goinyk/Shutterstock.com

FIGURE 4.17 Icebergs move as a result of wind and ocean currents. They can be very dangerous to ships, so their positions are reported and their probable courses estimated by an International Ice Patrol. The patrol was established in 1914 following the sinking of the *Titanic*.

It is also common knowledge that solid water (ice) floats on liquid water (see **Figure 4.17**). Nothing peculiar here—or is there? In fact, there is. Water, like most other liquids, increases in density as it is cooled. This means that a specific mass of liquid decreases in volume as its temperature is lowered. Unlike most liquids, water behaves this way only until it reaches a temperature of about 4°C, as shown by the data in **Table 4.10**. Then, its density decreases as it is cooled further. When its temperature reaches 0°C, water freezes and, in the process, undergoes a dramatic decrease in density. Put another way, a quantity of liquid water at 0°C expands significantly when it freezes to solid at 0°C. Thus, a specific volume of ice has a lower mass than the same volume of liquid water, so the ice floats on the water. Hydrogen bonds between water molecules are, once again, responsible. The strong hydrogen bonds orient water molecules into a very open three-dimensional crystal lattice when it freezes (see **Figure 4.16(c)**). This open lattice of the solid occupies more space than is occupied by the molecules in the liquid state.

TABLE 4.10 Water Density as a Function of Temperature

Temperature (°C)	Water Density (g/mL)
100	0.9586
80	0.9719
60	0.9833
40	0.9923
20	0.9982
10	0.9997
5	0.9999
4 (actually 3.98)	1.0000
2	0.9999
0 (liquid H_2O)	0.9998
0 (solid H_2O)	0.9170

Even though containers or engines might be ruptured or cracked if water is allowed to freeze in them, the overall effect of this characteristic of water is beneficial. If ice did not float, it would form on natural waters in the winter and sink to the bottom. Gradually, ponds, lakes, and other bodies of water would fill with ice. In the spring, the ice would melt from the top down because the heavier solid ice would stay under the water. As a result, most natural waters in areas that experience freezing winters would contain significant amounts of ice year-round. It would be a strange (and possibly hostile) environment for us and for wildlife.

The amount of heat required to melt a quantity of solid and the amount of heat required to vaporize a quantity of liquid also depend on the attractive forces between molecules. As expected, these are high for water, compared with the hydrogen compounds of the three other elements in group VIA(16). The beneficial results of these high values for water will be discussed in Chapter 6.

The forces between O_2 molecules, the lattice particles of solid oxygen, do not fit into any of the classifications we have discussed to this point. The O_2 molecule is not polar and contains no ionic or metallic bonds, and solid oxygen melts at much too low a temperature to fit into the category of a network solid. The forces between O_2 molecules are called **dispersion forces** and result from momentary nonsymmetric electron distributions in the molecules.

dispersion forces Very weak attractive forces acting between the particles of all matter. They result from momentary nonsymmetric electron distributions in molecules or atoms.

The nonbonding electrons in an O_2 molecule can be visualized as being uniformly distributed. However, there is a small statistical chance that, during their normal movement, more of the electrons will momentarily be on one side of a molecule than on the other. This condition causes the molecule to become dipolar for an instant. The resulting negative side of the dipole will tend to repel electrons of adjoining molecules and induce them also to become dipolar (they become induced dipoles). The original (statistical) dipole and all induced dipoles are then attracted to one another. This happens many times per second throughout the solid or liquid oxygen. The net effect is a weak dispersion force of attraction between the molecules. The net force is weak because it represents the average result of many weak, short-lived attractions per second between molecules.

Dispersion forces exist in all matter, but because they are very weak, their contribution is negligible when other, stronger forces are also present. Thus, solid water is held together by dispersion forces and hydrogen bonds, but the properties are almost entirely the result of the hydrogen bonds. The ease with which a dipole can be induced increases with the size of the particle (atoms or molecules). The larger the particle, the stronger the resulting dipolar attraction (dispersion force), and the harder to separate the particles by melting or boiling. Thus, we expect to find the melting and boiling points of the elements increase as we move down a group of the periodic table.

Example 4.19 The Behavior of Dispersion Forces

Illustrate the behavior of dispersion forces by using the information in **Table 4.11**.

Solution

The molecules increase in size in the order F_2, Cl_2, Br_2, I_2. The strength of dispersion forces increases in the same order, as shown in **Table 4.11** by the increases in melting and boiling points.

✔ **LEARNING CHECK 4.19** Using only the periodic table, predict which member of each of the following pairs of elements would have the higher melting and boiling points:

a. O and Se b. Sb and P c. He and Ne

TABLE 4.11 The Normal Melting and Boiling Points of Group VIIA(17) Elements

Substance	Melting Point (°C)	Boiling Point (°C)
F_2	−223	−188
Cl_2	−103	−34.6
Br_2	−7.2	58.8
I_2	113.9	184.3

The melting and boiling points in Example 4.19 indicate the variation in magnitude of dispersion forces. Similar variations are found for the other forces described in this section; sometimes their strengths overlap. For example, some metallic bonds are weaker than ionic bonds, whereas others are stronger. This is illustrated in **Figure 4.18**, which summarizes the relative strengths of interparticle forces.

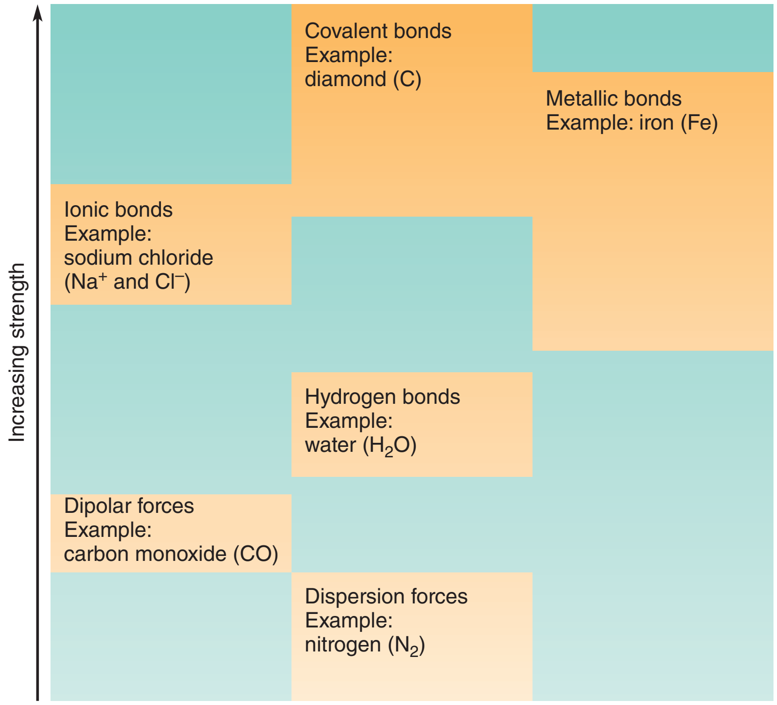


FIGURE 4.18 The relative strengths of interparticle forces.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Health Career Description

PARAMEDIC

Paramedics work in fast-paced critical-care situations. They provide lifesaving treatment and stabilize patients for transport to facilities where doctors take over the patients' care. Doctors rely on the paramedic's assessment to quickly understand what the patient needs when the transport is complete.

According to the U.S. Bureau of Labor Statistics, "Most EMTs and paramedics work full time. Their work can be physically strenuous and stressful, sometimes involving life-or-death situations." Paramedics must be able to establish patient-care priorities and make quick decisions.

Knowledge of chemistry and biochemistry is essential in understanding treatments for stabilizing patients and which medications are appropriate for various situations. A paramedic's proficiency in chemistry serves to ensure proper patient care, guard against drug interactions, and recognize potentially dangerous situations such as ketoacidosis or respiratory alkalosis.

Physical fitness is a job requirement. Paramedics are often expected to work on physical fitness at a gym during work hours. Career preparation varies from technical-college certificate programs to university associate degree programs. After completing the education for paramedic training, students will take a state licensure exam. Paramedics require state licenses in order to work—requirements vary by state. Employment opportunities for paramedics are growing at a rate of 7% per year.

Good paramedics should have excellent overall communication skills and knowledge of psychology, special populations (e.g., elderly, children, disabled) and be trained in substance abuse issues. Paramedics are primary communicators with patients and their families. They're often called on to diffuse emotional situations and bring a sense of calm and confidence when a scene is fraught with fear and anxiety. Communities rely on paramedics as frontline responders to keep their people safe and secure.

Sources: AAS in Paramedic Studies, GradMaps, Weber State University. Retrieved from: https://apps.weber.edu/gradmaps/getAttachment.aspx?MAP=2703&Att=703. March 13, 2020. Bureau of Labor Statistics, U.S. Department of Labor, Occupational Outlook Handbook, EMTs and Paramedics. Retrieved from: https://www.bls.gov/ooh/healthcare/emts-and-paramedics.htm March 13, 2020.

Concept Summary

4.1 Noble Gas Configurations

Learning Objective: Can you draw correct Lewis structures for atoms of representative elements?

- The lack of reactivity for noble gases led to the proposal that the electronic configurations of the noble gases represent stable configurations.
- These configurations, usually consisting of eight electrons in the valence shell, can be represented in several useful ways.

4.2 Ionic Bonding

Learning Objective: Can you use electronic configurations to determine the number of electrons gained or lost by atoms as they achieve noble gas electronic configurations?

- Ionic compounds are formed when reacting atoms gain or lose electrons to achieve a noble gas configuration of eight electrons in the valence shell.
- This octet rule predicts that atoms will be changed into charged particles called simple ions.
- Ions of opposite charge are attracted to each other.
- This attractive force is called an ionic bond.

4.3 Ionic Compounds

Learning Objective: Can you use the octet rule to correctly predict the ions formed during the formation of ionic compounds, and write correct formulas for binary ionic compounds containing a representative metal and a representative nonmetal?

- Oppositely charged ions group together to form compounds in ratios determined by the positive and negative charges of the ions.
- The formulas representing these ratios contain the lowest number of each ion possible in a proportion such that the total positive charges and total negative charges used are equal.

4.4 Naming Binary Ionic Compounds

Learning Objective: Can you correctly name binary ionic compounds?

- Binary ionic compounds contain a metal and a nonmetal.
- They are named by naming the metal, then adding the suffix *-ide* to the stem of the nonmetal.

4.5 The Smallest Unit of Ionic Compounds

Learning Objective: Can you determine formula weights for ionic compounds?

- Ionic compounds do not exist in the form of molecules but as three-dimensional arrangements of oppositely charged ions.
- The sum of the atomic weights of the elements in the formula of ionic compounds is called the formula weight and is used in calculations somewhat like those for the molecular weight of molecular compounds.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

4.6 Covalent Bonding

Learning Objective: Can you draw correct Lewis structures for covalent molecules?

- Elements with little or no tendency to gain or lose electrons often react and achieve noble gas electronic configurations by sharing electrons.
- Lewis structures are useful in representing electron sharing.
- Shared pairs of electrons exert an attractive force on both atoms that share them.
- The atoms are held together by this attraction to form a covalent bond.

4.7 Polyatomic Ions

Learning Objective: Can you draw correct Lewis structures for polyatomic ions?

- Polyatomic ions are groups of two or more covalently bonded atoms that carry a net electrical charge.
- They are conveniently represented using Lewis structures.

4.8 Shapes of Molecules and Polyatomic Ions

Learning Objective: Can you use VSEPR theory to predict the shapes of molecules and polyatomic ions?

- The shapes of many molecules and polyatomic ions can be predicted by using the valence-shell electron-pair repulsion (VSEPR) theory.
- According to the VSEPR theory, electron pairs in the valence shell of the central atom of a molecule or ion repel one another and become arranged so as to maximize their separation distances.
- The resulting arrangement determines the molecular or ionic shape when one or all of the electron pairs involved form bonds between the central atom and other atoms.

4.9 The Polarity of Covalent Molecules

Learning Objective: Can you use electronegativities to classify covalent bonds of molecules, and determine whether covalent molecules are polar or nonpolar?

- Shared electrons may be shared equally, or they may be attracted more strongly to one of the atoms they bond together.
- The tendency of a covalently bonded atom to attract shared electrons is called the electronegativity of the atom.
- Unequally shared bonding-electron pairs form polar covalent bonds.
- The extent of bond polarization can be estimated from the electronegativity differences between the bonded atoms.
- The higher the electronegativity difference, the more polar (or ionic) is the bond.
- Polar covalent bonds cause partial positive and negative charges to form within molecules.
- When these charges are symmetrically distributed in the molecule, it is said to be nonpolar.
- An unsymmetric distribution gives rise to a polar molecule.

4.10 More about Naming Compounds

Learning Objective: Can you write correct formulas for ionic compounds containing representative metals and polyatomic ions, and correctly name binary covalent compounds and compounds containing polyatomic ions?

- Binary covalent compounds are named using the name of the less electronegative element first, followed by the stem plus *-ide* of the more electronegative element.
- Greek prefixes are used to represent the number of each type of atom in molecules of the compounds.
- Ionic compounds that contain a metal ion (or ammonium ion) plus a polyatomic ion are named by first naming the metal (or ammonium ion) followed by the name of the polyatomic ion.

4.11 Other Interparticle Forces

Learning Objective: Can you relate melting and boiling points of pure substances to the strength and type of interparticle forces present in the substances?

- Forces other than ionic and covalent bonds are also known to hold the particles of some pure substances together in the solid and liquid states.
- These forces include metallic bonds, dipolar attractions, hydrogen bonds, and dispersion forces.
- The strength of the predominant force acting in a substance is indicated by the melting and boiling points of the substance.

Key Terms and Concepts

Binary compound (4.3)
Bond polarization (4.9)
Covalent bond (4.6)
Crystal lattice (4.5)
Dipolar force (4.11)
Dispersion force (4.11)
Double bond (4.6)
Electronegativity (4.9)
Formula weight (4.5)
Hydrogen bonding (4.11)
Ionic bond (4.2)
Isoelectronic (4.2)
Lattice site (4.5)
Lewis structure (4.1)
Metallic bond (4.11)
Network solids (4.11)
Nonpolar covalent bond (4.9)
Nonpolar molecule (4.9)
Octet rule (4.2)
Polar covalent bond (4.9)
Polar molecule (4.9)
Polyatomic ion (4.7)
Simple ion (4.2)
Triple bond (4.6)
VSEPR theory (4.8)

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Noble Gas Configurations (Section 4.1)

4.1 Refer to the group numbers of the periodic table and draw Lewis structures for atoms of the following:

a. potassium

b. barium

c. aluminum

d. bromine

4.2 Refer to the group numbers of the periodic table and draw Lewis structures for atoms of the following:

a. iodine

b. strontium

c. tin

d. sulfur

4.3 Write abbreviated electronic configurations for the following:

a. fluorine

b. element 37

c. selenium

d. silicon

4.4 Write abbreviated electronic configurations for the following:

a. tin

b. Cs

c. element number 49

d. strontium

4.5 Draw Lewis structures for the elements given in Exercise 4.3.

4.6 Draw Lewis structures for the elements given in Exercise 4.4.

4.7 Use the symbol E to represent an element in a general way and draw Lewis structures for atoms of the following:

a. Any group IIIA(13) element

b. Any group VIA(16) element

4.8 Use the symbol E to represent an element in a general way and draw Lewis structures for atoms of the following:

a. Any group IIA(2) element

b. Any group VA(15) element

Ionic Bonding (Section 4.2)

4.9 Indicate both the minimum number of electrons that would have to be added and the minimum number that would have to be removed to change the electronic configuration of each element listed in Exercise 4.3 to attain a noble gas configuration.

4.10 Indicate both the minimum number of electrons that would have to be added and the minimum number that would have to be removed to change the electronic configuration of each element listed in Exercise 4.4 to attain a noble gas configuration.

4.11 Use the periodic table and predict the number of electrons that will be lost or gained by the following elements as they change into simple ions. Write an equation using elemental symbols, ionic symbols, and electrons to represent each change.

a. Mg

b. silicon

c. element 53

d. sulfur

4.12 Use the periodic table and predict the number of electrons that will be lost or gained by the following elements as they change into simple ions. Write an equation using elemental symbols, ionic symbols, and electrons to represent each change.

a. Cs

b. oxygen

c. element number 7

d. iodine

4.13 Write a symbol for each of the following ions:

a. A bromine atom that has gained one electron

b. A sodium atom that has lost one electron

c. A sulfur atom that has gained two electrons

4.14 Write a symbol for each of the following ions:

a. A selenium atom that has gained two electrons

b. A rubidium atom that has lost one electron

c. An aluminum atom that has lost three electrons

4.15 Identify the element in period 2 that would form each of the following ions. E is used as a general symbol for an element.

a. E^-

b. E^{2+}

c. E^{3-}

d. E^+

4.16 Identify the element in period 3 that would form each of the following ions. E is used as a general symbol for an element.

a. E^{2-}

b. E^{3+}

c. E^+

d. E^-

4.17 Identify the noble gas that is isoelectronic with each of the following ions:

a. Mg^{2+}

b. Te^{2-}

c. N^{3-}

d. Be^{2+}

4.18 Identify the noble gas that is isoelectronic with each of the following ions:

a. Li^+

b. I^-

c. S^{2-}

d. Sr^{2+}

Ionic Compounds (Section 4.3)

4.19 Write equations to represent positive and negative ion formation for the following pairs of elements. Then write a formula for the ionic compound that results when the ions combine.

a. Ca and S

b. Mg and N

c. element numbers 19 and 17

4.20 Write equations to represent positive and negative ion formation for the following pairs of elements. Then write a formula for the ionic compound that results when the ions combine.

a. Ca and Cl

b. lithium and bromine

c. element numbers 12 and 16

4.21 Write the formula for the ionic compound formed from Ca^{2+} and each of the following ions:

a. Br^-

b. O^{2-}

c. S^{2-}

d. N^{3-}

4.22 Write the formula for the ionic compound formed from Ba^{2+} and each of the following ions:

a. Se^{2-}

b. P^{3-}

c. I^-

d. As^{3-}

4.23 Classify each of the following as a binary compound or not a binary compound:

a. HF

b. OF_2

c. H_2SO_4

d. H_2S

e. $MgBr_2$

4.24 Classify each of the following as a binary compound or not a binary compound:

a. PbO_2

b. $CuCl_2$

c. KNO_3

d. Be_3N_2

e. $CaCO_3$

Naming Binary Ionic Compounds (Section 4.4)

4.25 Name the following metal ions:

a. Ca^{2+}

b. K^+

c. Al^{3+}

d. Rb^+

4.26 Name the following metal ions:

a. Li^+

b. Mg^{2+}

c. Ba^{2+}

d. Cs^+

4.27 Name the following nonmetal ions:

a. Cl^-

b. N^{3-}

c. S^{2-}

d. Se^{2-}

4.28 Name the following nonmetal ions:

a. Br^-

b. O^{2-}

c. P^{3-}

d. F^-

4.29 Name the following binary ionic compounds:

a. Na_2O

b. $CaCl_2$

c. Al_2S_3

d. LiF

e. Ba_3N_2

4.30 Name the following binary ionic compounds:

a. SrS

b. CaF_2

c. $BaCl_2$

d. Li_2O

e. MgO

4.31 Name the following binary ionic compounds, using a Roman numeral to indicate the charge on the metal ion:

a. $CrCl_2$ and $CrCl_3$

b. CoS and Co_2S_3

c. FeO and Fe_2O_3

d. $PbCl_2$ and $PbCl_4$

4.32 Name the following binary ionic compounds, using a Roman numeral to indicate the charge on the metal ion:

a. PbO and PbO_2

b. CuCl and $CuCl_2$

c. Au_2S and Au_2S_3

d. CoO and Co_2O_3

4.33 Name the binary compounds of Exercise 4.31 by adding the endings -*ous* and -*ic* to indicate the lower and higher ionic charges of the metal ion in each pair of compounds. The non-English root for lead (Pb) is *plumb*-.

4.34 Name the binary compounds of Exercise 4.32 by adding the endings -*ous* and -*ic* to indicate the lower and higher ionic charges of the metal ion in each pair of compounds. The non-English root for gold (Au) is *aur*-, and that of lead (Pb) is *plumb*-.

4.35 Write formulas for the following binary ionic compounds:

a. manganese(II) chloride

b. iron(III) sulfide

c. chromium(II) oxide

d. iron(II) bromide

e. tin(II) chloride

4.36 Write formulas for the following binary ionic compounds:

- **a.** mercury(I) oxide
- **b.** lead(II) oxide
- **c.** platinum(IV) iodine
- **d.** copper(I) nitride
- **e.** cobalt(II) sulfide

The Smallest Unit of Ionic Compounds (Section 4.5)

4.37 Determine the formula weight in atomic mass units for each of the following binary ionic compounds:

- **a.** Na_2O
- **b.** FeO
- **c.** PbS_2
- **d.** $AlCl_3$

4.38 Determine the formula weight in atomic mass units for each of the following binary ionic compounds:

- **a.** NaBr
- **b.** CaF_2
- **c.** Cu_2S
- **d.** Li_3N

4.39 Identify the ions that would occupy lattice sites in a solid sample of each compound given in Exercise 4.37.

4.40 Identify the ions that would occupy lattice sites in a solid sample of each compound given in Exercise 4.38.

4.41 Calculate the mass in grams of positive ions and negative ions contained in 1 mol of each compound given in Exercise 4.37.

4.42 Calculate the mass in grams of positive ions and negative ions contained in 1 mol of each compound given in Exercise 4.38.

4.43 Calculate the number of positive ions and negative ions contained in 1.00 mol of each compound given in Exercise 4.37.

4.44 Calculate the number of positive ions and negative ions contained in 1.00 mol of each compound given in Exercise 4.38.

Covalent Bonding (Section 4.6)

4.45 Represent the following reaction using Lewis structures:

$$I + I \rightarrow I_2$$

4.46 Represent the following reaction using Lewis structures:

$$8S \rightarrow S_8 \text{ (the atoms form a ring)}$$

4.47 Represent the following molecules by Lewis structures:

- **a.** HF
- **b.** IBr
- **c.** PH_3 (each H atom is bonded to the P atom)
- **d.** $HClO_2$ (the O atoms are each bonded to the Cl, and the H is bonded to one of the O atoms)

4.48 Represent the following molecules by Lewis structures:

- **a.** CH_4 (each H atom is bonded to the C atom)
- **b.** CO_2 (each O atom is bonded to the C atom)
- **c.** H_2Se (each H atom is bonded to the Se atom)
- **d.** NH_3 (each H atom is bonded to the N atom)

Polyatomic Ions (Section 4.7)

4.49 Draw Lewis structures for the following polyatomic ions:

- **a.** ClO_3^- (each O atom is bonded to the Cl atom)
- **b.** CN^-
- **c.** CO_3^{2-} (each O atom is bonded to the C atom)

4.50 Draw Lewis structures for the following polyatomic ions:

- **a.** NH_4^+ (each H atom is bonded to the N atom)
- **b.** PO_4^{3-} (each O atom is bonded to the P atom)
- **c.** SO_3^{2-} (each O atom is bonded to the S atom)

Shapes of Molecules and Polyatomic Ions (Section 4.8)

4.51 Draw Lewis structures for the following molecules:

- **a.** O_3 (the O atoms are bonded together, like beads on a string)
- **b.** CS_2 (each S atom is bonded to the C atom)
- **c.** SeO_2 (each O atom is bonded to the Se atom)
- **d.** H_2SO_3 (each O atom is bonded to the S atom, and one H atom is bonded to each of two O atoms)

4.52* Predict the shape of each of the following molecules by first drawing a Lewis structure, then applying the VSEPR theory:

- **a.** H_2S (each H atom is bonded to the S atom)
- **b.** PCl_3 (each Cl atom is bonded to the P atom)
- **c.** OF_2 (each F atom is bonded to the O atom)
- **d.** SnF_4 (each F atom is bonded to the Sn atom)

4.53* Predict the shape of each of the following molecules by first drawing a Lewis structure, then applying the VSEPR theory:

- **a.** O_3 (see Exercise 4.51 for Lewis structure)
- **b.** SeO_2 (see Exercise 4.51 for Lewis structure)
- **c.** PH_3 (each H atom is bonded to the P atom)
- **d.** SO_3 (each O atom is bonded to the S atom)

4.54* Predict the shape of each of the following polyatomic ions by first drawing a Lewis structure, then applying the VSEPR theory:

- **a.** NO_2^- (each O is bonded to N)
- **b.** ClO_3^- (each O is bonded to Cl)
- **c.** CO_3^{2-} (each O is bonded to C)
- **d.** H_3O^+ (each H is bonded to O)

  Note the positive charge; compare with NH_4^+.

4.55* Predict the shape of each of the following polyatomic ions by first drawing a Lewis structure, then applying the VSEPR theory:

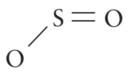
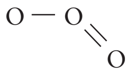
- **a.** NH_2^- (each H is bonded to N)
- **b.** PO_3^{3-} (each O is bonded to P)
- **c.** $BeCl_4^{2-}$ (each Cl is bonded to Be)
- **d.** ClO_4^- (each O is bonded to Cl)

The Polarity of Covalent Molecules (Section 4.9)

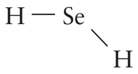
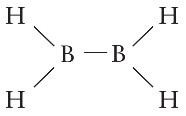
4.56 Use the periodic table and **Table 4.4** to determine which of the following bonds will be polarized. Show the resulting

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

charge distribution in those molecules that contain polarized bonds.

- **a.** $\mathrm{H{-}I}$
- **b.** 
- **c.** 

4.57 Use the periodic table and **Table 4.4** to determine which of the following bonds will be polarized. Show the resulting charge distribution in those molecules that contain polarized bonds.

- **a.** $\mathrm{Cl{-}F}$
- **b.** 
- **c.** 

4.58 Use **Table 4.4** and classify the bonds in the following compounds as nonpolar covalent, polar covalent, or ionic:

- **a.** LiBr
- **b.** HCl
- **c.** $\mathrm{PH_3}$ (each H is bonded to P)
- **d.** $\mathrm{SO_2}$ (each O is bonded to S)
- **e.** CsF

4.59 Use **Table 4.4** and classify the bonds in the following compounds as nonpolar covalent, polar covalent, or ionic:

- **a.** $\mathrm{MgI_2}$ (each I is bonded to Mg)
- **b.** $\mathrm{NCl_3}$ (each Cl is bonded to N)
- **c.** $\mathrm{H_2S}$ (each H is bonded to S)
- **d.** RbF
- **e.** SrO

4.60 On the basis of the charge distributions you drew for the molecules of Exercise 4.56, classify each of the molecules as polar or nonpolar.

4.61 On the basis of the charge distributions you drew for the molecules of Exercise 4.57, classify each of the molecules as polar or nonpolar.

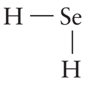
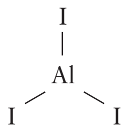
4.62 Use **Table 4.4** and predict the type of bond you would expect to find in compounds formed from the following elements:

- **a.** magnesium and chlorine
- **b.** carbon and hydrogen
- **c.** phosphorus and hydrogen

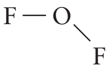
4.63 Use **Table 4.4** and predict the type of bond you would expect to find in compounds formed from the following elements:

- **a.** C and Br
- **b.** aluminum and chlorine
- **c.** nitrogen and oxygen

4.64* Show the charge distribution in the following molecules, and predict which are polar molecules:

- **a.** $\mathrm{C{\equiv}O}$
- **b.** 
- **c.** 

4.65* Show the charge distribution in the following molecules, and predict which are polar molecules:

- **a.** $\mathrm{S{=}C{=}S}$
- **b.** $\mathrm{H{-}C{\equiv}N}$
- **c.** 

More about Naming Compounds (Section 4.10)

4.66 Name the following binary covalent compounds:

- **a.** $\mathrm{PCl_3}$, used in making plasticisers and pesticides
- **b.** $\mathrm{N_2O}$, “laughing gas” anesthetic
- **c.** $\mathrm{CCl_4}$, once a popular solvent, now phased out because of health concerns
- **d.** $\mathrm{BF_3}$, a polymerization reaction catalyst
- **e.** $\mathrm{CS_2}$, used as an insecticide fumigant for grains, cereal mills, etc.

4.67 Name the following binary covalent compounds:

- **a.** $\mathrm{SiO_2}$, has many uses in tablet making in the pharmaceutical industry
- **b.** $\mathrm{SiF_4}$, found in volcanic plumes
- **c.** $\mathrm{B_2O_3}$, used in making borosilicate glass
- **d.** NO, a vasodilator
- **e.** $\mathrm{CBr_4}$, can damage liver and kidneys

4.68 Write formulas for the following binary covalent compounds:

- **a.** chlorine dioxide, used to disinfect water
- **b.** dinitrogen monoxide, “laughing gas” anesthetic
- **c.** sulfur dioxide, used to preserve dried foods
- **d.** carbon tetrachloride, once a popular solvent, now phased out because of health concerns

4.69 Write formulas for the following binary covalent compounds:

- **a.** sulfur hexafluoride, an ultrasound contrast agent
- **b.** silicon tetrachloride, an intermediate in the production of solar cells
- **c.** dinitrogen trioxide, a toxic gas
- **d.** sulfur trioxide, used in making sulfuric acid and explosives

4.70 Write the formulas and names for compounds composed of ions of the following metals and the indicated polyatomic ions:

- **a.** calcium and hypochlorite ion
- **b.** cesium and nitrite ion
- **c.** Mg and $\mathrm{SO_3{}^{2-}}$
- **d.** K and $\mathrm{Cr_2O_7{}^{2-}}$

4.71 Write the formulas and names for compounds composed of ions of the following metals and the indicated polyatomic ions:

- **a.** calcium and carbonate ion
- **b.** sodium and sulfate ion
- **c.** K^+ and $PO_4{}^{3-}$
- **d.** Mg^{2+} and $NO_3{}^-$

4.72 Write formulas for the following compounds:

- **a.** magnesium sulfite, used to remove SO_2 gas from industrial flue gases
- **b.** barium hydroxide, used to titrate weak acids
- **c.** calcium carbonate, used as a calcium dietary supplement
- **d.** ammonium sulfate, used in the purification of water and vaccine preparations
- **e.** lithium hydrogen carbonate, used to treat bipolar disorders

4.73 Write formulas for the following compounds:

- **a.** potassium hydroxide, can be used to dissolve warts and cuticles
- **b.** sodium carbonate, found in some toothpastes as an abrasive
- **c.** ammonium chloride, use as an expectorant in cough medicine
- **d.** sodium phosphate, commonly used to treat constipation
- **e.** calcium nitrate, used in wastewater treatments

4.74 Write a formula for the following compounds, using *M* with appropriate charges to represent the metal ion:

- **a.** Any group IA(1) element and $SO_3{}^{2-}$
- **b.** Any group IA(1) element and $C_2H_3O_2{}^-$
- **c.** Any metal that forms M^{2+} ions and $Cr_2O_7{}^{2-}$
- **d.** Any metal that forms M^{3+} ions and $PO_4{}^{3-}$
- **e.** Any metal that forms M^{3+} ions and $NO_3{}^-$

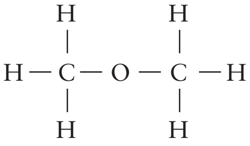
4.75 Write a formula for the following compounds, using *M* with appropriate charges to represent the metal ion:

- **a.** Any group IIA(2) element and $PO_4{}^{3-}$
- **b.** Any group IIA(2) element and $NO_3{}^-$
- **c.** Any metal that forms M^+ ions and $SO_4{}^{2-}$
- **d.** Any metal that forms M^{3+} ions and OH^-
- **e.** Any metal that forms M^{2+} ions and $HPO_4{}^{2-}$

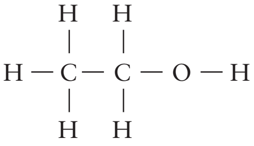
Other Interparticle Forces (Section 4.11)

4.76* The covalent compounds ethyl alcohol and dimethyl ether both have the formula C_2H_6O. However, the alcohol melts at −117.3°C and boils at 78.5°C, whereas the ether melts at −138.5°C and boils at −23.7°C. How could differences in forces between molecules be used to explain these observations?

4.77* The following structural formulas represent molecules of ethyl alcohol and dimethyl ether. Assign the correct name to each formula and explain how your choice is consistent with your answer to Exercise 4.76.



$$\begin{array}{ccccccccc} & & H & & & & H & & \\ & & | & & & & | & & \\ H & - & C & - & O & - & C & - & H \\ & & | & & & & | & & \\ & & H & & & & H & & \end{array}$$



$$\begin{array}{ccccccccc} & & H & & H & & & & \\ & & | & & | & & & & \\ H & - & C & - & C & - & O & - & H \\ & & | & & | & & & & \\ & & H & & H & & & & \end{array}$$

4.78 Describe the predominant forces that exist between molecules of the noble gases. Arrange the noble gases in a predicted order of increasing boiling point (lowest first) and explain the reason for the order.

4.79* Use the concept of interparticle forces to propose an explanation for the fact that CO_2 is a soft, low-melting solid (dry ice), whereas SiO_2 is a hard solid (sand). Focus on the nature of the particles that occupy lattice sites in the solid.

4.80 Table sugar, sucrose, melts at about 185°C. Which interparticle forces do you think are unlikely to be the predominant ones in the lattice of solid sucrose?

4.81 The formula for sucrose is $C_{12}H_{22}O_{11}$, where many of the hydrogens and oxygens are combined to form OH groups that are bonded to carbon atoms. What type of predominant interparticle bonding would you now propose for solid sucrose (see Exercise 4.80)?

Additional Exercises

4.82 Three atoms with an electronic configuration of $1s^1$ are covalently bonded to one atom with an electronic configuration of $1s^2\ 2s^2\ 2p^3$ to form a molecule. What is the formula of this molecule? Make a drawing to show how two of these molecules would hydrogen bond with each other.

4.83 Suppose an element from group IIA(2) and period 3 of the periodic table forms an ionic compound with the element that has an electronic configuration of $1s^2\ 2s^2\ 2p^5$. What would be the formula of the compound, and what would be the name of the compound?

4.84 What would be the mass in grams of 0.200 moles of the ionic compound formed when magnesium metal reacts with oxygen?

4.85 The ampere unit is used to describe the flow of electricity in an electrical circuit. One ampere is an amount of electricity corresponding to the flow of 6.2×10^{18} electrons past a point in a circuit in 1 second. In a hydrogen fuel cell, hydrogen atoms are dissociated into H^+ ions and electrons ($H \rightarrow H^+ + 1e^-$). How many grams of hydrogen must be dissociated each second in a fuel cell to produce 1.0 ampere of electricity?

4.86 If one atom of oxygen reacted with two atoms of nitrogen to form a molecule, what would be the formula of the molecule? Use **Table 4.4** and **Figure 4.13** to determine if the bond between the atoms is ionic or covalent. Also, name the compound that is formed.

Chemistry for Thought

4.87 Refer to **Figure 4.5** and answer the question in the caption. What other metals and nonmetals would you predict might react in a similar way?

4.88 The colors of some compounds, such as those shown in **Figure 4.6**, result from the presence of water in the compounds. Propose an experiment you could perform to see if this was true for the compounds shown in **Figure 4.6**.

4.89 Refer to **Figure 4.12**, and answer the question in the caption. Propose the shapes that would be assumed by a group of five balloons and by a group of six balloons.

4.90 Refer to **Figure 4.15**. Three of the compounds are highly colored (other than white). All the compounds consist of potassium and a polyatomic ion. If you have not yet done so, write formulas for the compounds and see if you can find

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

a characteristic of the polyatomic ions of the colored compounds that is not found in the white compounds.

4.91 Recall how a metal atom changes to form a positively charged metal ion. How do you think the sizes of a metal atom and a positive ion of the same metal will compare?

4.92 Recall how a nonmetal atom such as chlorine changes to form a negatively charged ion. How do you think the size of a nonmetal atom and a negatively charged ion of the same nonmetal will compare?

4.93 Neon atoms do *not* combine to form Ne_2 molecules. Explain.

4.94 Refer to **Figure 4.14** and answer the question in the caption. The balloon carries a negative charge. What would happen if a positively charged object was used in place of the balloon?

4.95 It has been found that NO is a vital biological molecule. Explain how NO forms when a fuel such as natural gas, CH_4, is burned in air at a high temperature.

5 Chemical Reactions

Nastasic/E+/Getty Images

Health Career Focus

CLINICAL LABORATORY TECHNICIAN

I'm naturally meticulous. Some might call me a perfectionist. I like working puzzles and getting the right answer. I like math—the world of numbers, measurement, and predictability. I have this knack for precision. It really comes in handy at work.

I've always liked watching science and true-crime shows that showed people working in laboratories wearing their protective gear, working with racks of tiny tubes and fancy droppers, and looking at slides under microscopes. Somehow, I knew a lab was the place for me—a place where "getting it right" really mattered. I wanted to use my talents, and this is how I could do it.

My university offered a Medical Laboratory Science (MLS) major—a perfect fit—because I got to work in medicine, but not so much on the "people" side of things, like a doctor working with patients, but in the medical laboratory—right where I belong.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Identify the reactants and products in written reaction equations, and balance the equations by inspection. **(Section 5.1)**
2. Assign oxidation numbers to elements in chemical formulas, and identify the oxidizing and reducing agents in redox reactions. **(Section 5.3)**
3. Classify reactions into the categories of redox or nonredox, then into the categories of decomposition, combination, single replacement, or double replacement. **(Sections 5.4–5.6)**
4. Write molecular equations in total ionic and net ionic forms. **(Section 5.7)**
5. Classify reactions as exothermic or endothermic. **(Section 5.8)**
6. Use the mole concept to do calculations based on chemical reaction equations. **(Section 5.9)**
7. Use the mole concept to do calculations based on the limiting-reactant principle. **(Section 5.10)**
8. Use the mole concept to do percentage-yield calculations. **(Section 5.11)**

IN PREVIOUS CHAPTERS, we introduced the terms *molecule*, *element*, *compound*, and *chemical change.* In Chapter 1, you learned that chemical changes result in the transformation of one or more substances into one or more new substances. The processes involved in such changes are called *chemical reactions.* In this chapter, you will learn to write and read chemical equations that represent chemical reactions, to classify reactions, and to do calculations based on the application of the mole concept to chemical equations.

5.1 Chemical Equations

Learning Objective 1 Identify the reactants and products in written reaction equations, and balance the equations by inspection.

A simple chemical reaction between elemental hydrogen and oxygen has been used to power the engines of a number of spacecraft, including the space shuttle, which was operated by the United States from 1981 to 2011 (see **Figure 5.1**). The products are water and much heat. For the moment, we will focus only on the substances involved; we will deal with the heat later. The reaction can be represented by a word equation:

Darryl Fonseka/Shutterstock.com

FIGURE 5.1 Liquid hydrogen in combination with liquid oxygen yields the highest efficiency of any known rocket propellant. Here, a space shuttle is shown about 5 seconds before launch, after the hydrogen-burning main engines have ignited but before the solid rocket boosters begin firing.

$$\text{hydrogen} + \text{oxygen} \rightarrow \text{water} \qquad (5.1)$$

The word equation gives useful information, including the reactants and products of the reaction. The **reactants** are the substances that undergo the chemical change; by convention, these are written on the left side of the equation. The **products**, or substances produced by the chemical change, are written on the right side of the equation. The reactants and products are separated by an arrow that points to the products. A plus sign (+) is used to separate individual reactants and products.

reactants of a reaction The substances that undergo chemical change during the reaction. They are written on the left side of the equation, representing the reaction.

products of a reaction The substances produced as a result of the reaction taking place. They are written on the right side of the equation, representing the reaction.

Word equations convey useful information, but the chemical equations used by chemists convey much more:

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(\ell) \qquad (5.2)$$

In this equation, the reactants and products are represented by molecular formulas that tell much more than the names used in the word equation. For example, it is apparent that both hydrogen and oxygen molecules are diatomic. The equation is also consistent with a fundamental law of nature called the **law of conservation of matter**. According to this law, atoms are neither created nor destroyed in chemical reactions but are rearranged to form new substances. Thus, atoms are conserved in chemical reactions, but molecules are not. The numbers written as coefficients to the left of the molecular formulas make the equation consistent with this law by making the total number of each kind of atom equal in the reactants and products. Note that coefficients of 1 are never written but are understood. Equations written this way are said to be **balanced**. In addition, the symbol in parentheses to the right of each formula indicates the state or form in which the substance exists. Thus, in Equation 5.2, the reactants hydrogen and oxygen (see **Figure 5.2**) are both in the form of gases (g), and the product water is in the form of a liquid (ℓ). Other common symbols you will encounter are (s) to designate a solid and (aq) to designate a substance dissolved in water. The symbol (aq) comes from the first two letters of *aqua,* the Latin word for water.

law of conservation of matter Atoms are neither created nor destroyed in chemical reactions.

balanced equation An equation in which the number of atoms of each element in the reactants is the same as the number of atoms of that same element in the products.

Wavebreakmedia/iStock/Getty Images

FIGURE 5.2 Oxygen therapy is prescribed for people who can't get enough oxygen on their own.

Example 5.1 Interpreting Equations

Determine the number of atoms of each type on each side of Equation 5.2.

Solution

The coefficient 2 written to the left of H_2 means that two hydrogen molecules with the formula H_2 are reacted. Since each molecule contains two hydrogen atoms, a total of four hydrogen atoms is represented. The coefficient to the left of O_2 is 1, even though it is not written in the equation. The oxygen molecule contains two atoms, so a total of two oxygen atoms is represented. The coefficient 2 written to the left of H_2O means that two molecules of H_2O are produced. Each molecule contains two hydrogen atoms and one oxygen atom. Therefore, the total number of hydrogen atoms represented is four, and the number of oxygen atoms is two. These are the same as the number of hydrogen and oxygen atoms represented in the reactants.

✔ **LEARNING CHECK 5.1** Determine the number of atoms of each type on each side of the following balanced equation:

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$$

When the identity and formulas of the reactants and products of a reaction are known, the reaction can be balanced by applying the law of conservation of matter.

Example 5.2 Writing Balanced Equations

Nitrogen dioxide (NO_2) is an air pollutant that is produced in part when nitric oxide (NO) reacts with oxygen gas (O_2). Write a balanced equation for the production of NO_2 by this reaction.

Solution

The reactants written to the left of the arrow will be NO and O_2. The product is NO_2:

$$NO(g) + O_2(g) \rightarrow NO_2(g) \tag{5.3}$$

A quick inspection shows that the reactants contain three oxygen atoms, whereas the product has just two. The number of nitrogen atoms is the same in both the reactants and the products. A practice sometimes resorted to by beginning chemistry students is to change the formula of oxygen gas to O by changing the subscript and to write

$$NO(g) + O(g) \rightarrow NO_2(g) \tag{5.4}$$

This is not allowed. The natural molecular formulas of any compounds or elements cannot be adjusted; they are fixed by the principles of chemical bond formation described in Chapter 4. All that can be done to balance a chemical equation is to change the coefficients of the reactants and products. In this case, inspection reveals that the following is a balanced form of the equation:

$$2NO(g) + O_2(g) \rightarrow 2NO_2(g) \tag{5.5}$$

Notice that the following forms of the equation are also balanced:

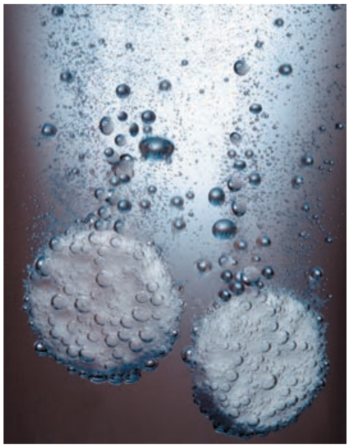
$$4NO(g) + 2O_2(g) \rightarrow 4NO_2(g) \tag{5.6}$$

and

$$NO(g) + \frac{1}{2}O_2(g) \rightarrow NO_2(g) \tag{5.7}$$

In Equation 5.6, the coefficients are double those used in Equation 5.5; in Equation 5.7, one coefficient is a fraction. The lowest possible whole-number coefficients are used in balanced equations. Thus, Equation 5.5 is the correct form.

✓ **LEARNING CHECK 5.2** Write and balance an equation that represents the reaction of sulfur dioxide (SO_2) with oxygen gas (O_2) to give sulfur trioxide (SO_3).



Colin Anderson Productions pty ltd/Stockbyte/Getty Images

FIGURE 5.3 A chemical reaction takes place when antacid tablets are dropped into water.

5.2 Types of Reactions

A large number of chemical reactions (see **Figure 5.3**) are known to occur; only a relatively small number of them will be studied in this book. This study is made easier by classifying the reactions according to certain characteristics. Such a classification scheme could be developed in a number of ways, but we have chosen to first classify reactions as being either oxidation–reduction (redox) reactions or nonredox reactions. As you will see, redox reactions are very important in numerous areas of study, including metabolism. Once reactions are classified as redox or nonredox, many can be further classified into one of several other categories, as shown in **Figure 5.4**. Notice that according to **Figure 5.4**, single-replacement, or substitution, reactions are redox reactions, whereas double-replacement, or metathesis, reactions are nonredox. Combination and decomposition reactions can be either redox or nonredox.

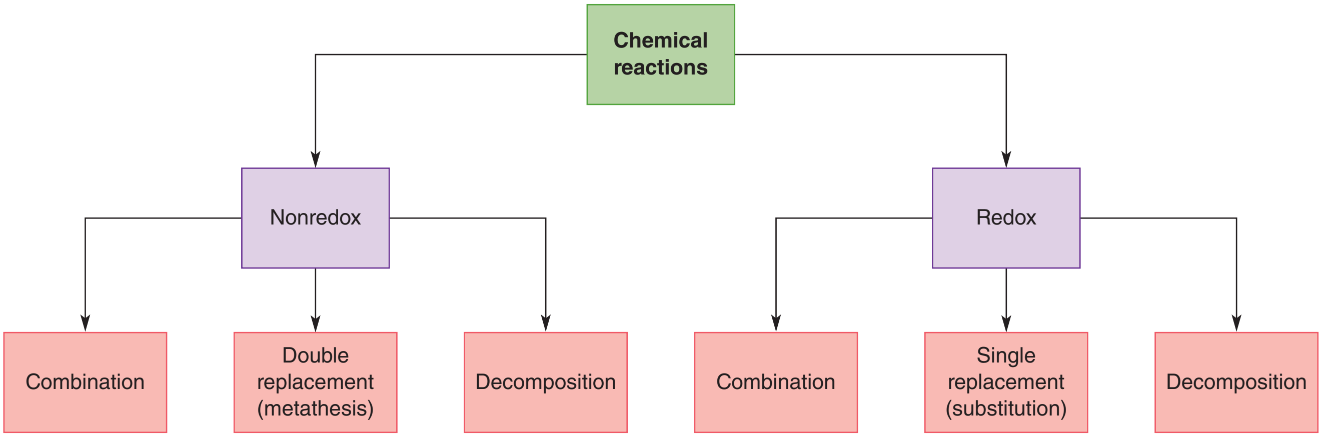


FIGURE 5.4 A classification of chemical reactions.

5.3 Redox Reactions

Learning Objective 2 Assign oxidation numbers to elements in chemical formulas, and identify the oxidizing and reducing agents in redox reactions.

Almost all elements react with oxygen to form oxides. The process is so common that the word *oxidation* was coined to describe it. Some examples are the rusting of iron,

$$4Fe(s) + 3O_2(g) \rightarrow 2Fe_2O_3(s) \qquad (5.8)$$

and the burning of hydrogen,

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(\ell) \qquad (5.9)$$

The reverse process, *reduction*, originally referred to the technique of removing oxygen from metal oxide ores to produce the free metal. Some examples are

$$CuO(s) + H_2(g) \rightarrow Cu(s) + H_2O(\ell) \qquad (5.10)$$

and

$$2Fe_2O_3(s) + 3C(s) \rightarrow 4Fe(s) + 3CO_2(g) \qquad (5.11)$$

Today, the words **oxidation** and **reduction** are used in a rather broad sense. **Table 5.1** contains most of the common meanings. To understand oxidation and reduction in terms of electron transfer and oxidation number (O.N.) change, you must become familiar with the concept of oxidation numbers.

Oxidation numbers, sometimes called **oxidation states**, are positive or negative numbers assigned to the elements in chemical formulas according to a specific set of rules. The following rules will be used; be sure to note that Rule 1 applies only to uncombined elements—that is, elements in their free state. Rules 2 through 7 apply to elements combined to form compounds or ions.

oxidation Originally, a process involving a reaction with oxygen. Today it means a number of things, including a process in which electrons are given up, hydrogen is lost, or an oxidation number increases.

reduction Originally, a process in which oxygen was lost. Today it means a number of things, including a process in which electrons are gained, hydrogen is accepted, or an oxidation number decreases.

oxidation numbers or oxidation states Positive or negative numbers assigned to the elements in chemical formulas according to a specific set of rules.

TABLE 5.1 Common Uses of the Terms *Oxidation* and *Reduction*

Term	Meaning
Oxidation	To combine with oxygen To lose hydrogen To lose electrons To increase in oxidation number
Reduction	To lose oxygen To combine with hydrogen To gain electrons To decrease in oxidation number

Rule 1. The oxidation number (O.N.) of any uncombined element is 0.
Examples: Al(0), O_2(0), Br_2(0), and Na(0)

Rule 2. The O.N. of a simple ion is equal to the charge on the ion.
Examples: $Na^+(+1)$, $Mg^{2+}(+2)$, $S^{2-}(-2)$, and $Br^-(-1)$

Rule 3. The O.N.s of combined group IA(1) and IIA(2) elements are +1 and +2, respectively.
Examples: Na_2CO_3(Na = +1), $Sr(NO_3)_2$ (Sr = +2), and $CaCl_2$ (Ca = +2)

Rule 4. The O.N. of combined hydrogen is +1.
Example: HCl (H = +1) and H_3PO_4 (H = +1)

Rule 5. The O.N. of combined oxygen is −2 except in peroxides, where it is −1.
Examples: CaO (O = −2), H_2SO_4 (O = −2), H_2O (O = −2), and H_2O_2 (O = −1)

Rule 6. The algebraic sum of the O.N.s of all atoms in a complete compound formula equals zero.

$$\begin{array}{lcccc}
\text{Examples: } K_2CO_3\text{:} & 2(\text{O.N. of K}) & + (\text{O.N. of C}) & + 3(\text{O.N. of O}) & = 0 \\
 & 2(+1) & +4 & +3(-2) & = 0 \\
 & +2 & +4 & +(-6) & = 0
\end{array}$$

$$\begin{array}{lccc}
HNO_2\text{: } (\text{O.N. of H}) & + (\text{O.N. of N}) & + 2(\text{O.N. of O}) & = 0 \\
+1 & +3 & +2(-2) & = 0 \\
+1 & +3 & +(-4) & = 0
\end{array}$$

Rule 7. The algebraic sum of the O.N.s of all atoms in a polyatomic ion is equal to the charge on the ion.

$$\begin{array}{lccc}
\text{Examples: } MnO_4^{\ -}\text{:} & (\text{O.N. of Mn}) & + 4(\text{O.N. of O}) & = -1 \\
 & +7 & +4(-2) & = -1 \\
 & +7 & +(-8) & = -1
\end{array}$$

$$\begin{array}{lccc}
HPO_4^{\ 2-}\text{: } (\text{O.N. of H}) & + (\text{O.N. of P}) & + 4(\text{O.N. of O}) & = -2 \\
+1 & +5 & +4(-2) & = -2 \\
+1 & +5 & +(-8) & = -2
\end{array}$$

Example 5.3 Assigning Oxidation Numbers

Formaldehyde (CH_2O, in part b) is a major component in embalming fluid.

a. Assign O.N.s to the blue element in each of the following:

CO_2, $NO_2^{\ -}$, H_2O, N_2, K^+

b. Assign O.N.s to each element in the following:

CO_2, $Mg(NO_3)_2$, $NO_3^{\ -}$, CH_2O

Solution

a. CO_2, O = −2 (Rule 5); NO_2^-, O = −2 (Rule 5); H_2O, H = +1 (Rule 4); N_2, N = 0 (Rule 1); K^+, K = +1 (Rule 2).

b. CO_2: The O.N. of O is −2 (Rule 5), and the O.N. of C can be calculated by using Rule 6 as follows:

$$\begin{aligned}(\text{O.N. of C}) + 2(\text{O.N. of O}) &= 0\\ (\text{O.N. of C}) + 2(-2) &= 0\\ (\text{O.N. of C}) + (-4) &= 0\end{aligned}$$

Therefore,

$$\text{O.N. of C} = +4$$

$Mg(NO_3)_2$: The O.N. of Mg is +2 (Rule 3), the O.N. of O is −2 (Rule 5), and the O.N. of N can be calculated by using Rule 6 as follows:

$$\begin{aligned}(\text{O.N. of Mg}) + 2(\text{O.N. of N}) + 6(\text{O.N. of O}) &= 0\\ (+2) + 2(\text{O.N. of N}) + 6(-2) &= 0\\ 2(\text{O.N. of N}) + 2 + (-12) &= 0\\ 2(\text{O.N. of N}) - 10 &= 0\\ 2(\text{O.N. of N}) &= 10\end{aligned}$$

Therefore,

$$\text{O.N. of N} = +5$$

NO_3^-: The O.N. of O is −2 (Rule 5), and the O.N. of N can be calculated by using Rule 7 as follows:

$$\begin{aligned}(\text{O.N. of N}) + 3(\text{O.N. of O}) &= -1\\ (\text{O.N. of N}) + 3(-2) &= -1\\ (\text{O.N. of N}) + (-6) &= -1\end{aligned}$$

Therefore,

$$\text{O.N. of N} = +5$$

Note that N has the same O.N. in NO_3^- and in $Mg(NO_3)_2$. This is expected because the polyatomic NO_3^- ion is present in $Mg(NO_3)_2$.

CH_2O: The O.N. of H is +1 (Rule 4), the O.N. of O is −2 (Rule 5), and the O.N. of C can be calculated by using Rule 6 as follows:

$$\begin{aligned}(\text{O.N. of C}) + 2(\text{O.N. of H}) + (\text{O.N. of O}) &= 0\\ (\text{O.N. of C}) + 2(+1) + (-2) &= 0\\ (\text{O.N. of C}) + 2 - 2 &= 0\end{aligned}$$

Therefore,

$$\text{O.N. of C} = 0$$

This example shows that an O.N. of 0 may be found for some combined elements as well as those in an uncombined state (Rule 1).

✔ **LEARNING CHECK 5.3** Assign O.N.s to each element in the following:

a. SO_3 b. $Ca(ClO_3)_2$ c. ClO_4^-

Now that you can assign O.N.s to the elements involved in reactions, you are ready to look at redox processes in terms of O.N.s and electron transfers. The reaction when sulfur is burned in oxygen is represented by the equation

$$S(s) + O_2(g) \rightarrow SO_2(g) \qquad (5.12)$$

You can see that this reaction represents an oxidation because sulfur has combined with oxygen (remember **Table 5.1**). When oxidation numbers are assigned to sulfur, the reactant S has an oxidation number of 0, while the S in the SO_2 product has an oxidation number of +4. Thus, the oxidation that has taken place resulted in an increase in the oxidation number of sulfur. Oxidation always corresponds to an increase in oxidation number.

The same conclusion is arrived at by thinking of oxidation numbers as charges. Thus, a sulfur atom with 0 charge is oxidized as it acquires a +4 charge. This change in charge results when the sulfur atom releases four electrons that have a −1 charge each. This leads to another definition of oxidation: Oxidation takes place when electrons are lost.

The oxygen of Equation 5.12 undergoes an oxidation number change from 0 in O_2 to −2 in SO_2. This decrease in oxidation number corresponds to a reduction of the oxygen. In terms of electrons, this same change is accomplished when each uncharged oxygen atom in the O_2 molecule accepts two electrons. Thus, the four electrons lost by sulfur as it was oxidized is the same total number accepted by the oxygen as it was reduced.

An oxidation process must always be accompanied by a reduction process, and all the electrons released during oxidation must be accepted during reduction. Thus, oxidation and reduction processes always take place simultaneously, hence the term redox. In redox reactions, the substance that is oxidized (and releases electrons) is called the **reducing agent** because it is responsible for reducing another substance. Similarly, the substance that is reduced (accepts electrons) is called the **oxidizing agent** because it is responsible for oxidizing another material (see **Figure 5.5**). These characteristics are summarized in **Table 5.2**.

reducing agent The substance that contains an element that is oxidized during a chemical reaction.

oxidizing agent The substance that contains an element that is reduced during a chemical reaction.

TABLE 5.2 Properties of Oxidizing and Reducing Agents

Oxidizing Agent	Reducing Agent
Gains electrons	Loses electrons
Oxidation number decreases	Oxidation number increases
Becomes reduced	Becomes oxidized

© Cengage Learning/Charles D. Winters

FIGURE 5.5 Combustion, the first reaction known to be carried out by humans, is a rapid redox reaction. Identify the oxidizing and reducing agents of the reaction.

A word of caution is appropriate here. Although electron transfers are a useful concept for understanding redox reactions involving covalent substances, it must be remembered that such transfers actually take place only during the formation of ionic compounds (see **Section 4.3**). In covalent substances, the electrons are actually shared (see **Section 4.6**). The oxidation number assignment rules that were given, as well as the electron-transfer idea, are based on the arbitrary practice of assigning shared electrons to the more electronegative element sharing them. However, it must be remembered that none of the atoms in covalent molecules actually acquire a net charge.

Example 5.4 Identifying Oxidizing and Reducing Agents

Determine oxidation numbers for each atom represented in the following equations and identify the oxidizing and reducing agents:

a. $4Al(s) + 3O_2(g) \longrightarrow 2Al_2O_3(s)$
b. $CO(g) + 3H_2(g) \longrightarrow H_2O(g) + CH_4(g)$
c. $S_2O_8^{2-}(aq) + 2I^-(aq) \longrightarrow I_2(aq) + 2SO_4^{2-}(aq)$

Solution

The O.N. under each elemental symbol was calculated by using the methods demonstrated in Example 5.3.

a. $\underset{0}{4Al} + \underset{0}{3O_2} \rightarrow 2\underset{+3}{Al_2}\ \underset{-2}{O_3}$

The O.N. of Al has changed from 0 to +3. Therefore, Al has been oxidized and is the reducing agent. The O.N. of O has decreased from 0 to −2. Oxygen has been reduced and is the oxidizing agent.

b. $\underset{+2}{C}\;\underset{-2}{O} + \underset{0}{3H_2} \rightarrow \underset{+1}{H_2}\;\underset{-2}{O} + \underset{-4}{C}\;\underset{+1}{H_4}$

The O.N. of H_2 increased from 0 to +1. H_2 has been oxidized and is the reducing agent. The O.N. of C has decreased from +2 to −4. Carbon has been reduced and could be called the oxidizing agent. However, when one element in a molecule or ion is the oxidizing or reducing agent, the convention is to refer to the entire molecule or ion by the appropriate term. Thus, carbon monoxide (CO) is the oxidizing agent.

c. $\underset{+7}{S_2}\;\underset{-2}{O_8}^{2-} + \underset{-1}{2I^-} \rightarrow \underset{0}{I_2} + \underset{+6}{2S}\;\underset{-2}{O_4}^{2-}$

The O.N. of I has increased from −1 to 0, and the I^- ion is the reducing agent. The O.N. of S in $S_2O_8^{2-}$ has decreased from +7 to +6. Thus, sulfur has been reduced, and $S_2O_8^{2-}$ is the oxidizing agent.

✔ **LEARNING CHECK 5.4** Assign oxidation numbers to each atom represented in the following equations and identify the oxidizing and reducing agents:

a. $Zn(s) + 2H^+(aq) \longrightarrow Zn^{2+}(aq) + H_2(g)$

b. $2KI(aq) + Cl_2(aq) \longrightarrow 2KCl(aq) + I_2(aq)$

c. $IO_3^-(aq) + 3HSO_3^-(aq) \longrightarrow I^-(aq) + 3HSO_4^-(aq)$

5.4 Decomposition Reactions

Learning Objective 3 Classify reactions into the categories of redox or nonredox, then into the categories of decomposition, combination, single replacement, or double replacement.

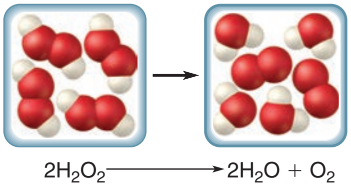


FIGURE 5.6 A decomposition reaction.

decomposition reaction A chemical reaction in which a single substance reacts to form two or more simpler substances.

In **decomposition reactions**, a single substance is broken down to form two or more simpler substances, as shown in **Figure 5.6**. In this and other "box" representations of reactions, the number of molecules in the boxes will not match the coefficients of the reaction equation. However, they will be in the correct proportions. In **Figure 5.6**, for example, the box on the left contains the same number of H_2O_2 molecules as the number of H_2O molecules on the right. Also, the number of H_2O molecules on the right is twice the number of O_2 molecules. The general form of the equation for a decomposition reaction is

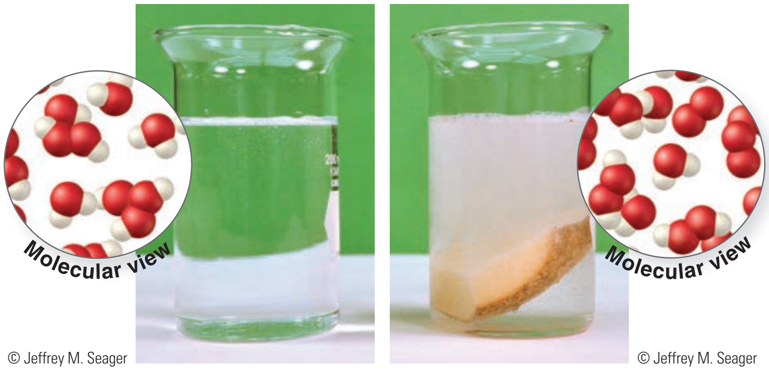
$$A \longrightarrow B + C \qquad (5.13)$$

Some decomposition reactions are also redox reactions, whereas others are not. Examples of decomposition reactions are given by Equations 5.14 and 5.15:

$$2HgO(s) \xrightarrow{\text{heat}} 2Hg(\ell) + O_2(g) \qquad (5.14)$$

$$CaCO_3(s) \xrightarrow{\text{heat}} CaO(s) + CO_2(g) \qquad (5.15)$$

Equation 5.14 represents the redox reaction that takes place when mercury(II) oxide (HgO) is heated. Mercury metal (Hg) and oxygen gas (O_2) are the products. This reaction was used by Joseph Priestley in 1774 when he discovered oxygen. Equation 5.15 represents a nonredox reaction used commercially to produce lime (CaO) by heating limestone ($CaCO_3$) to a high temperature. The decomposition of H_2O_2 represented by **Figure 5.3** is shown in **Figure 5.7**.



© Jeffrey M. Seager

© Jeffrey M. Seager

Figure 5.7 The decomposition of hydrogen peroxide. A solution of hydrogen peroxide (H_2O_2) in water (left) does not decompose rapidly until an enzyme catalyst from a piece of freshly cut potato is added (right). How can you tell that one of the products of the reaction is a gas?

5.5 Combination Reactions

Learning Objective 3 Classify reactions into the categories of redox or nonredox, then into the categories of decomposition, combination, single replacement, or double replacement.

combination reaction A chemical reaction in which two or more substances react to form a single substance.

Combination reactions are sometimes called *addition* or *synthesis reactions*. Their characteristic is that two or more substances react to form a single substance (see **Figure 5.8**). The reactants can be any combination of elements or compounds, but the product is always a compound. The general form of the equation is

$$A + B \longrightarrow C \qquad (5.16)$$

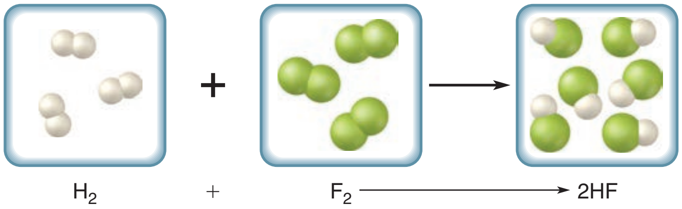


FIGURE 5.8 A combination reaction.

© Cengage Learning/Charles D. Winters

FIGURE 5.9 Magnesium metal burns in air to form magnesium oxide.

At high temperatures, a number of metals will burn and give off very bright light. This burning is a redox combination reaction, represented for magnesium metal by Equation 5.17 and shown in **Figure 5.9**.

$$2Mg(s) + O_2(g) \longrightarrow 2MgO(s) \qquad (5.17)$$

A nonredox combination reaction that takes place in the atmosphere contributes to the acid rain problem. An air pollutant called sulfur trioxide (SO_3) reacts with water vapor and forms sulfuric acid. The reaction is represented by Equation 5.18:

$$SO_3(g) + H_2O(\ell) \longrightarrow H_2SO_4(aq) \qquad (5.18)$$

5.6 Replacement Reactions

Learning Objective 3 Classify reactions into the categories of redox or nonredox, then into the categories of decomposition, combination, single replacement, or double replacement.

single-replacement reaction A chemical reaction in which an element reacts with a compound and displaces another element from the compound.

Single-replacement reactions, also called *substitution reactions*, are always redox reactions and take place when one element reacts with a compound and displaces another element from the compound. **Figure 5.10** represents a single-replacement reaction between elemental hydrogen and cuprous oxide. **Figure 5.11** shows a single-replacement reaction you can demonstrate in the laboratory by immersing a copper wire in a water

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

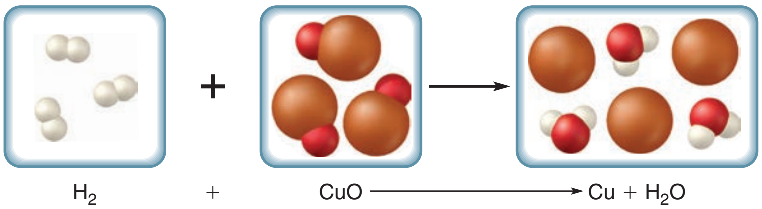
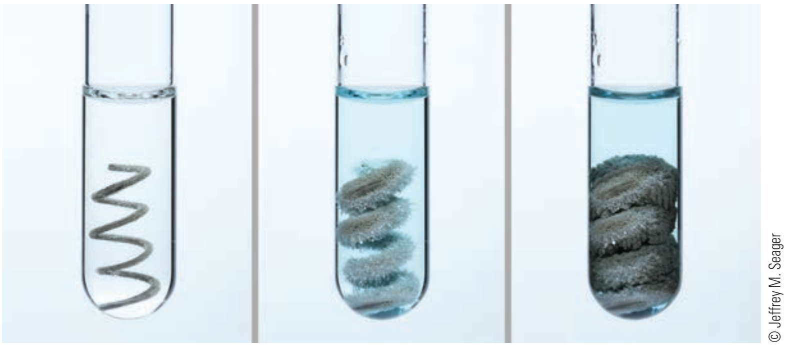


FIGURE 5.10 A single-replacement reaction.



© Jeffrey M. Seager

FIGURE 5.11 When a piece of copper wire (Cu) is placed in a solution of silver nitrate ($AgNO_3$) in water, crystals of silver metal (Ag) form on the wire, and the liquid solution that was originally colorless turns blue as copper nitrate [$Cu(NO_3)_2$] forms in solution. Write a balanced equation for this single-replacement reaction.

solution of silver nitrate. The general equation for a single-replacement reaction is shown in Equation 5.19.

$$A + BX \longrightarrow B + AX \tag{5.19}$$

This type of reaction is useful in a number of processes used to obtain metals from their oxide ores. Iron, for example, can be obtained by reacting iron(III) oxide ore (Fe_2O_3) with carbon. The carbon displaces the iron from the oxide, and carbon dioxide is formed. The equation for the reaction is

$$3C(s) + 2Fe_2O_3(s) \longrightarrow 4Fe(s) + 3CO_2(g) \tag{5.20}$$

Double-replacement reactions, also called *metathesis reactions*, are never redox reactions. These reactions, represented in **Figure 5.12**, often take place between substances dissolved in water. The general Equation 5.21 shows the partner-swapping characteristic of these reactions:

double-replacement reaction A chemical reaction in which two compounds react and exchange partners to form two new compounds.

$$AX + BY \longrightarrow BX + AY \tag{5.21}$$

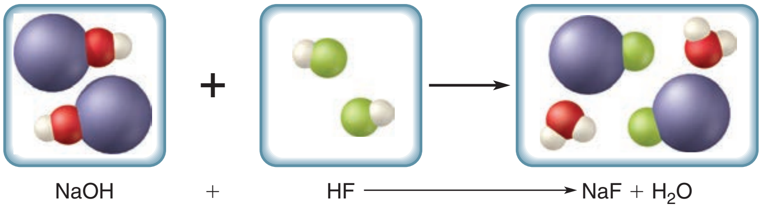


FIGURE 5.12 A double-replacement, or metathesis, reaction.

The reaction that takes place when a base is used to neutralize an acid is a good example of a double-replacement reaction:

$$HCl(aq) + NaOH(aq) \longrightarrow NaCl(aq) + H_2O(\ell) \tag{5.22}$$

Example 5.5 Classifying Reactions

Nitrogen gas (N_2, part c) is used for cryosurgery removal of some cancers and skin lesions and also for the storage of tissues and cells at cryogenic temperatures.

Classify each of the reactions represented by the following equations as redox or nonredox. Further classify them as decomposition, combination, single-replacement, or double-replacement reactions.

a. $SO_2(g) + H_2O(\ell) \rightarrow H_2SO_3(aq)$
b. $2K(s) + 2H_2O(\ell) \rightarrow 2KOH(aq) + H_2(g)$
c. $N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$
d. $BaCl_2(aq) + Na_2CO_3(aq) \rightarrow BaCO_3(s) + 2NaCl(aq)$

Solution

The O.N. under each elemental symbol was calculated by using the methods demonstrated in Example 5.3.

a. $\underset{+4}{S}\,\underset{-2}{O_2} + \underset{+1}{H_2}\,\underset{-2}{O} \rightarrow \underset{+1}{H_2}\,\underset{+4}{S}\,\underset{-2}{O_3}$

No O.N. changes take place; therefore, the reaction is nonredox. Because two substances combine to form a third, the reaction is a combination reaction.

b. $2\underset{0}{K} + 2\underset{+1}{H_2}\,\underset{-2}{O} \rightarrow 2\underset{+1}{K}\,\underset{-2}{O}\,\underset{+1}{H} + \underset{0}{H_2}$

The O.N. of K increases from 0 to +1 and that of H decreases from +1 to 0. The reaction is a redox reaction. Because K displaces H, it is a single-replacement reaction.

c. $\underset{0}{N_2} + 3\underset{0}{H_2} \rightarrow 2\underset{-3}{N}\,\underset{+1}{H_3}$

The O.N.s of both N and H change; therefore, the reaction is a redox reaction. Two substances combine to form a third, so it is a combination reaction.

d. $\underset{+2}{Ba}\,\underset{-1}{Cl_2} + \underset{+1}{Na_2}\,\underset{+4}{C}\,\underset{-2}{O_3} \rightarrow \underset{+2}{Ba}\,\underset{+4}{C}\,\underset{-2}{O_3} + 2\underset{+1}{Na}\,\underset{-1}{Cl}$

No changes in O.N. occur. The reaction is nonredox and is an example of a double-replacement, or partner-swapping, reaction.

✔ **LEARNING CHECK 5.5** Classify each of the reactions represented by the following equations as redox or nonredox. Further classify them as decomposition, combination, single-replacement, or double-replacement reactions.

a. $2HI(g) \rightarrow H_2(g) + I_2(g)$
b. $2H_2O_2(aq) \rightarrow 2H_2O(\ell) + O_2(g)$ (note: H_2O_2 is a peroxide)
c. $NaCl(aq) + AgNO_3(aq) \rightarrow AgCl(s) + NaNO_3(aq)$
d. $4P(s) + 5O_2(g) \rightarrow 2P_2O_5(s)$
e. $2NaI(aq) + Cl_2(aq) \rightarrow 2NaCl(aq) + I_2(aq)$

5.7 Ionic Equations

Learning Objective 4 Write molecular equations in total ionic and net ionic forms.

molecular equation An equation written with each compound represented by its formula.

total ionic equation An equation written with all soluble ionic substances represented by the ions they form in solution.

Many of the reactions of interest in the course you are taking occur between compounds or elements dissolved in water. Ionic compounds and some polar covalent compounds break apart (dissociate) into ions when they are dissolved in water. Thus, a water solution of sodium hydroxide (NaOH), an ionic compound, does not contain molecules of NaOH but, rather, contains equal numbers of sodium ions (Na^+) and hydroxide ions (OH^-). Covalently bonded hydrogen chloride, HCl, dissolves readily in water to form H^+ and Cl^- ions. Equations for reactions between substances that form ions in solution can be written in several ways. For example, Equation 5.22 contains three substances that form ions, HCl, NaOH, and NaCl. Equation 5.22 is written in the form of a **molecular equation** in which each compound is represented by its formula. This same reaction, when represented by a **total ionic equation**, becomes

$$H^+(aq) + Cl^-(aq) + Na^+(aq) + OH^-(aq) \rightarrow Na^+(aq) + Cl^-(aq) + H_2O(\ell) \qquad (5.23)$$

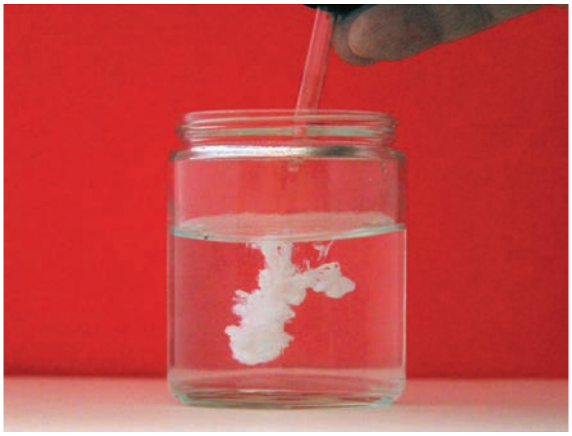
In this equation each ionic compound is shown dissociated into ions, the form it takes when it is dissolved in water. Some of the ions appear as both reactants and products. These so-called **spectator ions** do not actually undergo any changes in the reaction. Because of this, they are dropped from the equation when it is written as a **net ionic equation**:

spectator ions The ions in a total ionic reaction that are not changed as the reaction proceeds. They appear in identical forms on the left and right sides of the equation.

net ionic equation An equation that contains only un-ionized or insoluble materials and ions that undergo changes as the reaction proceeds. All spectator ions are eliminated.

$$H^+(aq) + OH^-(aq) \rightarrow H_2O(\ell) \tag{5.24}$$

The net ionic equation makes the partner-swapping characteristics of this double-replacement reaction less obvious, but it does emphasize the actual chemical changes that take place. **Figure 5.13** shows an experiment in which an ionic reaction occurs.



© Mike Slabaugh

FIGURE 5.13 The liquid in the large container is a solution of solid sodium chloride (NaCl) in water. The liquid being added is a solution of solid silver nitrate ($AgNO_3$) in water. When the two liquids are mixed, an insoluble white solid forms. The solid is silver chloride (AgCl). Write the molecular, total ionic, and net ionic equations for the reaction.

Example 5.6 Writing Reaction Equations

Sodium sulfate (Na_2SO_4) in combination with other salts is used to cleanse the colon (bowel) before a colonoscopy.

Write equations for the following double-replacement reaction in total ionic and net ionic forms. Note that barium sulfate ($BaSO_4$) does not dissolve in water and should not be written in dissociated form. All other compounds are ionic and soluble in water.

$$Na_2SO_4(aq) + BaCl_2(aq) \rightarrow BaSO_4(s) + 2NaCl(aq)$$

Solution

Total ionic:

$$2Na^+(aq) + SO_4^{2-}(aq) + Ba^{2+}(aq) + 2Cl^-(aq) \rightarrow BaSO_4(s) + 2Na^+(aq) + 2Cl^-(aq)$$

Net ionic:

$$SO_4^{2-}(aq) + Ba^{2+}(aq) \rightarrow BaSO_4(s)$$

The Na^+ and Cl^- ions appear in equal numbers as reactants and products. Thus, they are spectator ions and are not shown in the net ionic equation.

✔ **LEARNING CHECK 5.6** Write equations for the following reactions in total ionic and net ionic forms. Consider all ionic compounds to be soluble except $CaCO_3$ and $BaSO_4$, and remember that covalent molecules do not form ions when they dissolve.

a. $2NaI(aq) + Cl_2(aq) \rightarrow 2NaCl(aq) + I_2(aq)$
b. $CaCl_2(aq) + Na_2CO_3(aq) \rightarrow 2NaCl(aq) + CaCO_3(s)$
c. $Ba(OH)_2(aq) + H_2SO_4(aq) \rightarrow 2H_2O(\ell) + BaSO_4(s)$

HEALTH CONNECTIONS 5.1

Add Color to Your Diet

Scientific evidence accumulated during the 1990s suggested that diets rich in fruits and vegetables had a protective effect against a number of different types of cancer. Studies showed that simply increasing the levels of vitamins and minerals in the diet did not provide the increased protection. This led to research into the nature of other substances found in fruits and vegetables that are important for good health. As a result of this research, a number of chemical compounds found in plants and called *phytonutrients* have been shown to be involved in the maintenance of healthy tissues and organs. The mechanism for their beneficial action in the body is not understood for all phytonutrients, but a significant number are known to work as antioxidants that stop harmful oxidation reactions from occurring.

vm/iStock/Getty Images

Fruits and vegetables are often rich in beneficial compounds called phytonutrients.

5.8 Energy and Reactions

Learning Objective 5 Classify reactions as exothermic or endothermic.

Besides changes in composition, energy changes accompany all chemical reactions. The equation for the reaction between hydrogen and oxygen given at the beginning of this chapter (Equation 5.2) can also be written

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(g) + \text{energy} \qquad (5.25)$$

Most of the energy of this reaction appears as heat, but the energy released or absorbed during chemical changes can take many forms including sound, electricity, light, high-energy chemical bonds, and motion. Some of these forms are discussed in detail in later chapters, but here the focus will be on energy in general, and it will be expressed in calories or joules, as if it all took the form of heat.

On the basis of heat, Equation 5.25 can be written

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(g) + 115.6\text{ kcal } (483.7\text{ kJ}) \qquad (5.26)$$

This equation assumes that the hydrogen and oxygen are gases, and when they react, the water produced is also a gas (vapor). According to Equation 5.26, whenever 2 mol of water vapor is formed from 2 mol of hydrogen gas and 1 mol of oxygen gas, 115.6 kcal, or 483.7 kJ, of energy is also released.

exothermic reaction A reaction that liberates heat.

endothermic reaction A reaction that absorbs heat.

The reaction represented by Equation 5.26 is an example of an **exothermic** (heat out) **reaction**, in which heat is released as the reaction takes place. In **endothermic** (heat in) **reactions**, heat is absorbed. A reaction of this type is utilized in emergency cold packs, which consist of a small plastic pouch of liquid sealed inside a larger pouch that also contains a solid substance. When the large pouch is squeezed firmly, the small pouch of liquid breaks, the liquid and solid react, heat is absorbed, and the liquid contents of the larger pouch become cold. This reaction is described in more detail in Chapter 7.

5.9 The Mole and Chemical Equations

Learning Objective 6 Use the mole concept to do calculations based on chemical reaction equations.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The mole concept introduced in **Section 2.6** and applied to chemical formulas in **Section 2.7** can also be used to calculate mass relationships in chemical reactions. The study of such mass relationships is called **stoichiometry** (see **Figure 5.14**), a word derived from the Greek *stoicheion* (element) and *metron* (measure).

stoichiometry The study of mass relationships in chemical reactions.

Stoichiometry calculations require that balanced equations be used for the reactions being studied. Consider the following equation for the redox reaction that takes place when methane (CH_4), a major constituent of natural gas, is burned:

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(\ell) \tag{5.27}$$

Remember, coefficients in balanced equations refer to the formula that follows the coefficient. With this in mind, note that the following statement is consistent with this balanced equation:

1. 1 CH_4 molecule + 2 O_2 molecules → 1 CO_2 molecule + 2 H_2O molecules

This statement indicates that one molecule of CH_4 gas reacts with two molecules of O_2 gas and produces one molecule of CO_2 gas plus two molecules of H_2O liquid. Put another way, according to this reaction equation, the number of O_2 molecules that react with CH_4 will be equal to twice the number of CH_4 molecules that react. We remember that 1 mol of any kind of molecule is equal to 6.02×10^{23} molecules. Thus, 1 mol of CH_4 is equal to 6.02×10^{23} CH_4 molecules. As shown earlier, the number of O_2 molecules that will react with CH_4 will be twice the number of CH_4 molecules that react. Thus, the number of O_2 molecules that will react with 6.02×10^{23} CH_4 molecules is $2(6.02 \times 10^{23})$. Remembering that 6.02×10^{23} molecules is 1 mol of molecules leads to the conclusion that 1 mol of CH_4 molecules will react with 2 mol of O_2 molecules. We note that the numbers 1 and 2 are identical to the coefficients of the CH_4 and O_2 in the balanced equation. This leads to the conclusion that the coefficients in reaction equations can be interpreted as the number of moles of reactants and products involved in the reaction, which leads to the following statement for the reaction of CH_4 with O_2:

The History Collection/Alamy Stock Photo

FIGURE 5.14 Jeremias Richter, a German chemist, introduced the word *stoichiometry* in 1792.

2. 1 mol $CH_4(g)$ + 2 mol $O_2(g)$ → 1 mol $CO_2(g)$ + 2 mol $H_2O(\ell)$

In general, any balanced reaction equation can be interpreted this way, where the coefficients of the equation become the number of moles of reactants and products involved in the reaction.

The fact used earlier that 1 mol of any substance is equal to 6.02×10^{23} particles of the substance leads to statement 3 given below for the reaction of CH_4 with O_2:

3. 6.02×10^{23} CH_4 molecules + $2(6.02 \times 10^{23})$ O_2 molecules →
6.02×10^{23} CO_2 molecules + $2(6.02 \times 10^{23})$ H_2O molecules

Application of the fact that 1 mol of a compound has a mass in grams equal to the molecular weight of the compound leads to statement 4 given below for the reaction:

4. 16.0 g CH_4 + 2(32.0) g O_2 → 44.0 g CO_2 + 2(18.0) g H_2O

Statements 2, 3, and 4 are all based on the mole definition, and are very useful in solving numerical problems involving balanced reaction equations and the factor-unit method described earlier in **Section 1.9**. Any two quantities from statements 2, 3, and 4 can be used to form factors that can be used to solve problems. For example, the following factors are just four of the many that can be obtained from statements 2, 3, and 4 by combining various quantities from the statements:

$$\frac{2 \text{ mol } O_2}{1 \text{ mol } CH_4} \qquad \frac{16.0 \text{ g } CH_4}{44.0 \text{ g } CO_2} \qquad \frac{2(18.0) \text{ g } H_2O}{6.02 \times 10^{23} \text{ } CH_4 \text{ molecules}} \qquad \frac{1 \text{ mol } CH_4}{44.0 \text{ g } CO_2}$$

Suppose you were asked this question: How many moles of CO_2 could be formed by reacting together 2 mol of CH_4 and 4 mol of O_2? Statement 2 can be used to solve this problem quickly. We see that the amounts reacted correspond to twice the amounts represented by Statement 2. Thus, 2 mol of CO_2 would be formed, which is also twice

HEALTH CONNECTIONS 5.2

Teeth Whitening

Tooth enamel is the hardest substance in the human body. At a microscopic level, it is made up of tiny rods of hard calcium phosphate. The enamel occurs in two layers of a tooth. The top white layer covers a second yellow layer, so a normal tooth appears to be white in color. Teeth become more yellow in color when substances are applied to them that cause the inner yellow layer to darken. The antibiotic tetracycline and large amounts of fluoride stain teeth by this mechanism. Teeth also become stained by the frequent use of tobacco or highly colored beverages such as coffee, tea, or colored soft drinks. Such stains become permanent when colored organic material fills the space between the calcium phosphate rods that make up the enamel.

Perhaps it is ego-driven, but the process called "teeth whitening" has become quite popular. Four options for this process are now available: whitening done by professionals, the use of dentist-prescribed medications, over-the-counter medications, and so-called natural methods. With the exception of the natural method, all the methods involve the use of hydrogen peroxide (H_2O_2), which is an oxidizing agent that breaks down the colored organic material that fills the spaces between the calcium phosphate rods of tooth enamel. The natural method uses malic acid found in fruit to whiten the teeth. This method includes the requirement to eat an apple or some strawberries each day.

Spotmatik Ltd/Shutterstock.com

Teeth whitening has become a popular procedure.

the amount represented by Statement 2. However, many stoichiometric problems cannot be solved quite as readily, so it is helpful to learn a general approach that works well for many problems of this type. This approach is based on the factor-unit method described earlier in **Section 1.9**. The needed factors are obtained from Statements 2, 3, and 4.

Example 5.7 Interpreting Equations

The following questions are based on Equation 5.27.

a. How many moles of oxygen gas (O_2) will be required to react with 1.72 mol of methane (CH_4)?

b. How many grams of H_2O will be produced when 1.09 mol of CH_4 reacts with an excess of O_2?

c. How many grams of O_2 must react with excess CH_4 to produce 8.42 g of carbon dioxide (CO_2)?

Solution a.

The steps to follow in the factor-unit method are as follows (see **Section 1.9**):

1. Write down the known or given quantity. It will include both a number and a unit.
2. Leave working space, and set the known quantity equal to the unit of the unknown quantity.
3. Multiply the known quantity by a factor such that the unit of the known quantity is canceled and the unit of the unknown quantity is generated.
4. After the units on each side of the equation match, do the necessary arithmetic to get the final answer.

In this problem, the known quantity is 1.72 mol of CH_4, and the unknown quantity has the unit of mol O_2.

STEP 1: $1.72\ \text{mol CH}_4$

STEP 2: $1.72\ \text{mol CH}_4 \qquad\qquad = \text{mol O}_2$

STEP 3: $1.72\ \cancel{\text{mol CH}_4} \times \dfrac{2\ \text{mol O}_2}{1\ \cancel{\text{mol CH}_4}} = \text{mol O}_2$

The factor

$$\frac{2\ \text{mol O}_2}{1\ \text{mol CH}_4}$$

was used because it properly canceled the unit of the known and generated the unit of the unknown.

STEP 4: $(1.72)\left(\dfrac{2\ \text{mol O}_2}{1}\right) = 3.44\ \text{mol O}_2$

The answer contains the proper number of significant figures because the 2 and 1 of the factor are exact numbers (see **Section 1.8**).

Solution b.

STEP 1: $1.09\ \text{mol CH}_4$

STEP 2: $1.09\ \text{mol CH}_4 \qquad\qquad = \text{g H}_2\text{O}$

STEP 3: $1.09\ \cancel{\text{mol CH}_4} \times \dfrac{2(18.0)\ \text{g H}_2\text{O}}{1\ \cancel{\text{mol CH}_4}} \qquad = \text{g H}_2\text{O}$

STEP 4: $1.09 \times \dfrac{2(18.0)\ \text{g H}_2\text{O}}{1} = 39.24\ \text{g H}_2\text{O} = 39.2\ \text{g H}_2\text{O}$

The answer was rounded to three significant figures to match the three in 1.09 and 18.0 g of H_2O. The 1 and 2 are exact counting numbers.

Solution c.

STEP 1: $8.42\ \text{g CO}_2$

STEP 2: $8.42\ \text{g CO}_2 \qquad\qquad = \text{g O}_2$

STEP 3: $8.42\ \cancel{\text{g CO}_2} \times \dfrac{2(32.0)\ \text{g O}_2}{44.0\ \cancel{\text{g CO}_2}} \qquad = \text{g O}_2$

STEP 4: $8.42 \times \dfrac{2(32.0)\ \text{g O}_2}{44.0} = 12.2472\ \text{g O}_2 = 12.2\ \text{g O}_2$

The answer was rounded to three significant figures to match the three in 8.42, 32.0 g of O_2, and the 44.0. The 2 is an exact counting number.

✔ **LEARNING CHECK 5.7** The following reaction equation is balanced:

$$N_2(g) + 3H_2(g) \longrightarrow 2NH_3(g)$$

a. Write statements equivalent to statements 2, 3, and 4 based on this equation.
b. Calculate the number of mol of NH_3 that would be produced if 2.11 mol of H_2 was reacted with excess N_2.
c. Calculate the number of g of N_2 required to react with 9.47 g H_2.

5.10 The Limiting Reactant

Learning Objective 7 Use the mole concept to do calculations based on the limiting-reactant principle.

Nearly everyone is familiar with two characteristics of automobiles. They stop running when they run out of gasoline, and they stop running when the air intake to the engine becomes clogged. Most people also know that gasoline and air are mixed, and the mixture is burned inside the automobile engine. However, the combustion reaction occurs only as long as both reactants, gasoline and air, are present. The reaction (and engine) stops when gasoline is absent, despite the presence of ample amounts of air. And the reaction stops when air is absent, even though plenty of gasoline is available.

The behavior of the auto engine illustrates the **limiting-reactant principle** that a chemical reaction will take place only as long as all necessary reactants are present. The reaction will stop when one of the reactants, the **limiting reactant**, is used up. According to this principle, the amount of product formed depends on the amount of limiting reactant present because the reaction will stop (and no more product will form) when the concentration of the limiting reagent used up remains negligible. This is represented in **Figure 5.15** for the reaction $F_2(g) + H_2(g) \rightarrow 2HF(g)$.

limiting-reactant principle The amount of product possible is determined by the amount of each reactant present and the combining ratio.

limiting reactant The reactant that is completely used up first in a reaction, based on the amount of each reactant initially present and the combining ratio. It is the reactant that determines the amount of product formed.

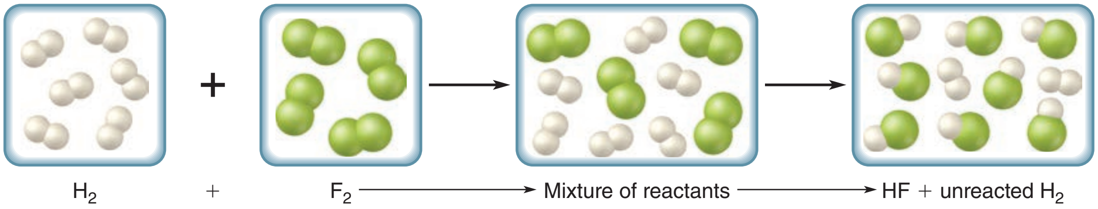


FIGURE 5.15 The limiting reactant is used up in a reaction.

Example 5.8 Identifying Limiting Reactants

Methane (CH_4), hydrogen, and carbon dioxide are all produced in the gut and contribute to most of the volume of flatus.

A mixture containing 20.0 g of CH_4 and 100.0 g of O_2 is ignited and burns according to Equation 5.27, which is repeated here: $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(\ell)$. What substances will be found in the mixture after the reaction stops?

Solution

The task is to identify the limiting reactant. It will be completely used up, and the other reactant will be found mixed with the products (CO_2 and H_2O) after the reaction stops. A simple way to identify the limiting reactant is to find out which reactant will give the least amount of products. To do this, two problems must be solved, one in which the known quantity is 20.0 g of CH_4 and one in which the known quantity is 100.0 g of O_2. In each case, the theoretical amount of CO_2 produced is calculated, although the same information would be obtained by solving for the amount of water produced.

$$20.0\ \cancel{\text{g}}\ \cancel{\text{CH}_4} \times \frac{44.0\ \text{g CO}_2}{16.0\ \cancel{\text{g}}\ \cancel{\text{CH}_4}} = 55.0\ \text{g CO}_2$$

$$100.0\ \cancel{\text{g}}\ \cancel{\text{O}_2} \times \frac{44.0\ \text{g CO}_2}{2(32.0)\ \cancel{\text{g}}\ \cancel{\text{O}_2}} = 68.75\ \text{g CO}_2 = 68.8\ \text{g CO}_2$$

Since the 20.0 g of CH_4 produces the smaller amount of CO_2, CH_4 is the limiting reactant. Therefore, the final mixture will contain the products CO_2 and H_2O and the leftover O_2.

Example 5.9 Working with Limiting Reactants

Copper is essential to living organisms as a trace dietary mineral.

The reaction shown in **Figure 5.11** was carried out by a student who wanted to produce some silver metal. The equation for the reaction is

$$Cu(s) + 2AgNO_3(aq) \rightarrow 2Ag(s) + Cu(NO_3)_2(aq)$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The student dissolved 17.0 g of $AgNO_3$ in distilled water, then added 8.50 g of copper metal, Cu, to the resulting solution. What mass of silver metal, Ag, was produced?

Solution

The limiting reactant must be identified because it will determine the amount of silver produced. To find the limiting reactant, we calculate the theoretical amount of silver produced by each reactant. The reactant that will produce the smallest mass of silver is the limiting reactant, and the mass of silver calculated for it is the amount produced by the reaction.

$$17.0\ \cancel{\text{g}}\ \cancel{\text{AgNO}_3} \times \frac{2(108)\ \text{g Ag}}{2(170)\ \cancel{\text{g}}\ \cancel{\text{AgNO}_3}} = 10.8\ \text{g Ag}$$

$$8.50\ \cancel{\text{g}}\ \cancel{\text{Cu}} \times \frac{2(108)\ \text{g Ag}}{63.6\ \cancel{\text{g}}\ \cancel{\text{Cu}}} = 28.8679\ \text{g Ag} = 28.9\ \text{g Ag}$$

We see that the $AgNO_3$ is the limiting reactant, and it will produce 10.8 g of Ag.

✔ **LEARNING CHECK 5.8** Refer to the reaction used for Learning Check 5.7. Assume that 2.00 mol of H_2 and 15.5 g of N_2 are reacted. What is the maximum mass of ammonia (NH_3) that can be produced? Which reactant is the limiting reactant?

5.11 Reaction Yields

Learning Objective 8 Use the mole concept to do percentage-yield calculations.

In **Sections 5.9** and **5.10**, calculations were done to determine how much product could be obtained from the reaction of specified amounts of reactants. In many instances, the amount determined by such calculations would be greater than the amount produced by reacting the specified reactants in a laboratory. Does this mean matter is destroyed when reactions are actually done in the laboratory? No, this would violate the law of conservation of matter, a fundamental law of nature. Less product might be obtained because some of the reactants form compounds other than the desired product. Such reactions are called **side reactions**. Carbon dioxide gas, CO_2, is produced when carbon-containing fuels burn in an ample supply of oxygen. However, a side reaction produces toxic carbon monoxide gas, CO, when the oxygen supply is limited.

side reactions Reactions that do not give the desired product of a reaction.

Another cause of less product than expected might be poor laboratory technique resulting in such things as losses when materials are transferred from one container to another. Whatever the cause, the mass of product obtained in an experiment is called the *actual yield*, and the mass calculated according to the methods of **Sections 5.9** and **5.10** is called the *theoretical yield*. The **percentage yield** is the actual yield divided by the theoretical yield multiplied by 100 (see **Section 1.10**):

percentage yield The percentage of the theoretical amount of a product actually produced by a reaction.

$$\%\ \text{yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100 \tag{5.28}$$

Example 5.10 Calculating Percentage Yields

Urea is a waste product of many living organisms and is the major carbon compound in human urine.

A chemist wants to produce urea (N_2CH_4O) by reacting ammonia (NH_3) and carbon dioxide (CO_2). The balanced equation for the reaction is

$$2NH_3(g) + CO_2(g) \rightarrow N_2CH_4O(s) + H_2O(\ell)$$

The chemist reacts 5.11 g of NH_3 with excess CO_2 and isolates 3.12 g of solid N_2CH_4O. Calculate the percentage yield of the experiment.

STUDY TOOLS 5.1

Help with Oxidation Numbers

Assigning oxidation numbers is a task that seems to be straightforward, but mistakes caused by carelessness often show up when it is done on exams. You can minimize such mistakes by using a systematic approach to the task.

- First, have the seven rules for assigning oxidation numbers (see **Section 5.3**) well in mind.
- Then, use an organized method such as the boxlike approach (shown below to assign an oxidation number to the Mn in Mn_2O_3). In this approach, we begin with an oxidation number that is given by one of the rules (O is −2 according to Rule 5):

Each Mn must be +3 because two Mn give +6 total.

Rule 6: Sum of total O.N. of Mn and O = 0.

$$\begin{tikzcd} \mathrm{Mn}_2 & \mathrm{O}_3 \arrow[d] \\ +3 & -2 \arrow[d] \\ +6 \arrow[u] & -6 \arrow[l] \end{tikzcd}$$

Rule 5: O.N. of O = −2.

Total O.N. for three O's = −6

- Follow the arrows in a clockwise direction to solve for the O.N. of each atom of Mn (+3 is correct). Remember that oxidation numbers are reported for individual atoms. For example, the total oxidation number due to Mn atoms is +6, but because there are two atoms of Mn in the formula, the oxidation number for each atom is just +3.

Solution

First, the theoretical yield must be calculated. Because this involves only masses of reactants and products, statements 2 and 4 based on the balanced equation will be used:

$$2NH_3(g) + CO_2(g) \rightarrow N_2CH_4O(s) + H_2O(\ell)$$

2. $$2 \text{ mol } NH_3(g) + 1 \text{ mol } CO_2(g) \rightarrow 1 \text{ mol } N_2CH_4O(s) + 1 \text{ mol } H_2O(\ell)$$

4. $$2(17.0) \text{ g } NH_3 + 44.0 \text{ g } CO_2 \rightarrow 60.0 \text{ g } N_2CH_4O + 18.0 \text{ g } H_2O$$

The known quantity is 5.11 g of NH_3, and the unit of the unknown quantity of N_2CH_4O is "g". The needed factor will come from statement 4.

STEP 1 $5.11 \text{ g } NH_3$

STEP 2 $5.11 \text{ g } NH_3 \qquad = \text{ g } N_2CH_4O$

STEP 3 $5.11 \cancel{\text{g } NH_3} \times \dfrac{60.0 \text{ g } N_2CH_4O}{2(17.0) \cancel{\text{g } NH_3}} \qquad = \text{ g } N_2CH_4O$

STEP 4 $5.11 \times \dfrac{60.0 \text{ g } N_2CH_4O}{2(17.0)} = 9.0176 \text{ g } N_2CH_4O = 9.02 \text{ g } N_2CH_4O$

The actual yield was 3.12 g, so the percentage yield is

$$\% \text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100 = \frac{3.12 \text{ g}}{9.02 \text{ g}} \times 100 = 34.5898\% = 34.6\%$$

✔ LEARNING CHECK 5.9

a. A chemist isolates 17.43 g of product from a reaction that has a calculated theoretical yield of 21.34 g. What is the percentage yield?

b. Lime (CaO) is produced by heating calcium carbonate. The equation for the reaction is $CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$. Suppose 510.0 g of $CaCO_3$ is heated, and 235 g of CaO is isolated after the reaction mixture cools. What is the percentage yield for the reaction?

Health Career Description

CLINICAL LABORATORY TECHNICIAN

Clinical laboratory technicians typically work under clinical technologists, who may in turn work under a medical laboratory scientist. Clinical laboratory technician is a career that may be entered with an associate of science degree; whereas, the laboratory technologist and medical laboratory scientist careers require a bachelor's degree.

According to the Bureau of Labor Statistics, clinical laboratory technologists and technicians typically do the following:

- Analyze body fluids, such as blood, urine, and tissue samples, and record normal or abnormal findings.
- Study blood samples for use in transfusions by identifying the number of cells, the cell morphology or the blood group, blood type, and compatibility with other blood types.
- Operate sophisticated laboratory equipment, such as microscopes and cell counters.
- Use automated equipment and computerized instruments capable of performing a number of tests at the same time.
- Log data from medical tests and enter results into a patient's medical record.
- Discuss results and findings of laboratory tests and procedures with physicians.

"Both technicians and technologists perform tests and procedures that physicians and surgeons, or other healthcare personnel, prescribe. However, technologists perform more complex tests and laboratory procedures than technicians do. For example, technologists may prepare specimens and perform detailed manual tests, whereas technicians perform routine tests that may be more automated. Clinical laboratory technicians usually work under the general supervision of clinical laboratory technologists or laboratory managers."

Clinical laboratory technicians and technologists are close partners with physicians in the diagnosis of disease. They provide essential feedback about patient status through laboratory testing. Their precise work is crucial to proper diagnosis and treatment of patients.

Concept Summary

5.1 Chemical Equations

Learning Objective: Can you identify the reactants and products in written reaction equations, and balance the equations by inspection?

- Chemical reactions are conveniently represented by equations.
- Reacting substances are called reactants.
- The substances produced are called products.
- The reactants and products are written in terms of formulas.
- Coefficients are placed before reactant and product formulas to balance the equation.
- A balanced equation satisfies the law of conservation of matter.

5.2 Types of Reactions

Learning Objective: Can you name the different types of reactions?

- To facilitate their study, reactions are classified into the general categories redox and nonredox.
- They are then further classified as decomposition, combination, single-replacement, or double-replacement reactions.

5.3 Redox Reactions

Learning Objective: Can you assign oxidation numbers to elements in chemical formulas, and identify the oxidizing and reducing agents in redox reactions?

- Reactions in which reactants undergo oxidation or reduction are called redox reactions.
- Oxidation and reduction are indicated conveniently by the oxidation number changes that occur.
- Oxidation numbers are assigned according to a specific set of rules.
- A substance is oxidized when the oxidation number of a constituent element increases.
- It is reduced when the oxidation number of a constituent element decreases.

5.4 Decomposition Reactions

Learning Objective: Can you classify reactions into the categories of redox or nonredox, then into the categories of decomposition, combination, single replacement, or double replacement?

- Decomposition reactions are characterized by one substance reacting to give two or more products.
- Decomposition reactions can be redox or nonredox.

5.5 Combination Reactions

Learning Objective: Can you classify reactions into the categories of redox or nonredox, then into the categories of decomposition, combination, single replacement, or double replacement?

- Combination reactions are characterized by two or more reactants that form a single compound as a product.
- Combination reactions can be redox or nonredox.
- They can also be called addition or synthesis reactions.

5.6 Replacement Reactions

Learning Objective: Can you classify reactions into the categories of redox or nonredox, then into the categories of decomposition, combination, single replacement, or double replacement?

- Single-replacement reactions, sometimes called substitution reactions, are always redox reactions.
- One element reacts with a compound and displaces another element from the compound.
- Double-replacement reactions, also called metathesis reactions, are always nonredox reactions.
- They can be recognized by their partner-swapping characteristics.

5.7 Ionic Equations

Learning Objective: Can you write molecular equations in total ionic and net ionic forms?

- Many water-soluble compounds separate (dissociate) into ions when dissolved in water.
- Reactions of such materials can be represented by molecular equations:
  - in which no ions are shown.
  - total ionic equations in which all ions are shown.
  - or net ionic equations in which only ions actually undergoing a change are shown.

5.8 Energy and Reactions

Learning Objective: Can you classify reactions as exothermic or endothermic?

- Energy changes accompany all chemical reactions.
- The energy can appear in a variety of forms, but heat is a common one.
- Exothermic reactions liberate heat.
- Endothermic reactions absorb heat.

5.9 The Mole and Chemical Equations

Learning Objective: Can you use the mole concept to do calculations based on chemical reaction equations?

- The mole concept, when applied to chemical equations, yields relationships that can be used to obtain factors for doing factor-unit calculations.

5.10 The Limiting Reactant

Learning Objective: Can you use the mole concept to do calculations based on the limiting-reactant principle?

- The limiting reactant is the reactant present in a reaction in an amount that determines the maximum amount of product that can be made.
- Factor-unit calculations can be used to determine which reactant is limiting.

5.11 Reaction Yields

Learning Objective: Can you use the mole concept to do percentage-yield calculations?

- The mass of product isolated after a reaction is often less than the mass theoretically possible.
- The ratio of the actual isolated mass (actual yield) to the calculated theoretical yield multiplied by 100 is the percentage yield.

Key Terms and Concepts

Balanced equation (5.1)
Combination reaction (5.5)
Decomposition reaction (5.4)
Double-replacement reaction (5.6)
Endothermic reaction (5.8)
Exothermic reaction (5.8)
Law of conservation of matter (5.1)
Limiting reactant (5.10)
Limiting-reactant principle (5.10)
Molecular equation (5.7)
Net ionic equation (5.7)
Oxidation (5.3)
Oxidation number (oxidation state) (5.3)
Oxidizing agent (5.3)
Percentage yield (5.11)
Products of a reaction (5.1)
Reactants of a reaction (5.1)
Reducing agent (5.3)
Reduction (5.3)
Side reactions (5.11)
Single-replacement reaction (5.6)
Spectator ions (5.7)
Stoichiometry (5.9)
Total ionic equation (5.7)

Key Equations

1. Decomposition reaction—one substance changes into two or more new substances (**Section 5.4**):	$A \longrightarrow B + C$	Equation 5.13
2. Combination reaction—two or more substances react to produce one new substance (**Section 5.5**):	$A + B \longrightarrow C$	Equation 5.16
3. Single-replacement reaction—one element reacts with a compound to produce a new compound and new element (**Section 5.6**):	$A + BX \longrightarrow B + AX$	Equation 5.19

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

4. Double-replacement reaction—partner-swapping reaction (**Section 5.6**):	$AX + BY \rightarrow BX + AY$	Equation 5.21
5. Percentage yield (**Section 5.11**):	$\%\ \text{yield} = \dfrac{\text{actual yield}}{\text{theoretical yield}} \times 100$	Equation 5.28

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Chemical Equations (Section 5.1)

5.1 Identify the reactants and products in each of the following reaction equations:

- **a.** $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$
- **b.** $2Al(s) + 3Cl_2(g) \rightarrow 2AlCl_3(s)$
- **c.** methane + water → carbon monoxide + hydrogen
- **d.** copper(II) oxide + hydrogen → copper + water

5.2 Identify the reactants and products in each of the following reaction equations:

- **a.** $H_2(g) + Cl_2(g) \rightarrow 2HCl(g)$
- **b.** $2KClO_3(s) \rightarrow 2KCl(s) + 3O_2(g)$
- **c.** magnesium oxide + carbon → magnesium + carbon monoxide
- **d.** ethane + oxygen → carbon dioxide + water

5.3 Identify which of the following are consistent with the law of conservation of matter. For those that are not, explain why they are not.

- **a.** $Fe(s) + O_2(g) \rightarrow Fe_2O_3(s)$
- **b.** $2Na_3PO_4(aq) + 3MgCl_2(aq) \rightarrow Mg_3\,(PO_4)_2(s) + 6NaCl(aq)$
- **c.** 3.20 g oxygen + 3.21 g sulfur → 6.41 g sulfur dioxide
- **d.** $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$

5.4 Identify which of the following are consistent with the law of conservation of matter. For those that are not, explain why they are not.

- **a.** $ZnS(s) + O_2(g) \rightarrow ZnO(s)+SO_2(g)$
- **b.** $Cl_2(aq) + 2I^-(aq) \rightarrow I_2(aq) + 2Cl^-(aq)$
- **c.** 1.50 g oxygen + 1.50 g carbon → 2.80 g carbon monoxide
- **d.** $2C_2H_6(g) + 7O_2(g) \rightarrow 4CO_2(g) + 6H_2O(g)$

5.5 Determine the number of atoms of each element on each side of the following equations and decide which equations are balanced:

- **a.** $3Pb(NO_3)_2(aq) + 2AlBr_3(aq) \rightarrow 3PbBr_2(s) + 2Al(NO_3)_3(aq)$
- **b.** $K(s) + H_2O(\ell) \rightarrow KOH(aq) + H_2(g)$
- **c.** $CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$
- **d.** $Ba(ClO_3)_2(aq) + H_2SO_4(aq) \rightarrow 2HClO_3(aq) + BaSO_4(s)$

5.6 Determine the number of atoms of each element on each side of the following equations and decide which equations are balanced:

- **a.** $Ag(s) + Cu(NO_3)_2(aq) \rightarrow Cu(s) + AgNO_3(aq)$
- **b.** $2N_2O(g) + 3O_2(g) \rightarrow 4NO_2(g)$
- **c.** $Mg(s) + O_2(g) \rightarrow 2MgO(s)$
- **d.** $H_2SO_4(aq) + Ca(OH)_2(aq) \rightarrow CaSO_4(s) + 2H_2O(\ell)$

5.7 Balance the following equations:

- **a.** $Li_3N(s) \rightarrow Li(s) + N_2(g)$
- **b.** $Cu_2O(s) + O_2(g) \rightarrow CuO(s)$
- **c.** $Zn(s) + HNO_3(aq) \rightarrow Zn(NO_3)_2(aq) + H_2(g)$
- **d.** $K_2SO_4(aq) + BaCl_2(aq) \rightarrow BaSO_4(s) + KCl(aq)$
- **e.** dinitrogen monoxide → nitrogen + oxygen
- **f.** dinitrogen pentoxide → nitrogen dioxide + oxygen
- **g.** $P_4O_{10}(s) + H_2O(\ell) \rightarrow H_4P_2O_7(aq)$
- **h.** $CaCO_3(s) + HCl(aq) \rightarrow CaCl_2(aq) + H_2O(\ell) + CO_2(g)$

5.8 Balance the following equations:

- **a.** $KClO_3(s) \rightarrow KCl(s) + O_2(g)$
- **b.** $C_2H_6(g) + O_2(g) \rightarrow CO_2(g) + H_2O(\ell)$
- **c.** nitrogen + oxygen → dinitrogen pentoxide
- **d.** $MgCl_2(s) + H_2O(g) \rightarrow MgO(s) + HCl(g)$
- **e.** $CaH_2(s) + H_2O(\ell) \rightarrow Ca(OH)_2(s) + H_2(g)$
- **f.** $Al(s) + Fe_2O_3(s) \rightarrow Al_2O_3(s) + Fe(s)$
- **g.** aluminum + bromine → aluminum bromide
- **h.** $Hg_2(NO_3)_2(aq) + NaCl(aq) \rightarrow Hg_2Cl_2(s) + NaNO_3(aq)$

Redox Reactions (Section 5.3)

5.9 Assign oxidation numbers to the blue element in each of the following formulas:

- **a.** $CaCO_3$
- **b.** H_2Se
- **c.** Ca_2^+
- **d.** Cl_2
- **e.** Na_2CrO_4
- **f.** PO_4^{3-}

5.10 Assign oxidation numbers to the blue element in each of the following formulas:

- **a.** $HClO$
- **b.** $NaNO_2$
- **c.** N_2

d. $Ca(ClO)_2$
e. Al^{3+}
f. N_2O_5

5.11 Find the element with the highest oxidation number in each of the following formulas:

a. N_2O_5
b. $KHCO_3$
c. $NaOCl$
d. $NaNO_3$
e. $HClO_4$
f. $Ca(NO_3)_2$

5.12 Find the element with the highest oxidation number in each of the following formulas:

a. $Na_2Cr_2O_7$
b. $K_2S_2O_3$
c. HNO_3
d. P_2O_5
e. $Mg(ClO_4)_2$
f. $HClO_2$

5.13 For each of the following equations, indicate whether the blue element has been oxidized, reduced, or neither oxidized nor reduced.

a. $2Mg(s) + O_2(g) \rightarrow 2MgO(s)$
b. $CuO(s) + H_2(g) \rightarrow Cu(s) + H_2O(g)$
c. $Ag^+(aq) + Cl^-(aq) \rightarrow AgCl(s)$
d. $BaCl_2(aq) + H_2SO_4(aq) \rightarrow BaSO_4(s) + 2HCl(aq)$
e. $Zn(s) + 2H^+(aq) \rightarrow Zn^{2+}(aq) + H_2(g)$

5.14 For each of the following equations, indicate whether the blue element has been oxidized, reduced, or neither oxidized nor reduced.

a. $4Al(s) + 3O_2(g) \rightarrow 2Al_2O_3(s)$
b. $SO_2(g) + H_2O(\ell) \rightarrow H_2SO_3(aq)$
c. $2KClO_3(s) \rightarrow 2KCl(s) + 3O_2(g)$
d. $2CO(g) + O_2(g) \rightarrow 2CO_2(g)$
e. $2Na(s) + 2H_2O(\ell) \rightarrow 2NaOH(aq) + H_2(g)$

5.15 Assign oxidation numbers to each element in the following equations and identify the oxidizing and reducing agents:

a. $H_2(g) + Cl_2(g) \rightarrow 2HCl(g)$
b. $H_2O(g) + CH_4(g) \rightarrow CO(g) + 3H_2(g)$
c. $CuO(s) + H_2(g) \rightarrow Cu(s) + H_2O(g)$
d. $B_2O_3(s) + 3Mg(s) \rightarrow 2B(s) + 3MgO(s)$
e. $Fe_2O_3(s) + CO(g) \rightarrow 2FeO(s) + CO_2(g)$
f. $Cr_2O_7^{2-}(aq) + 2H^+(aq) + 3Mn^{2+}(aq) \rightarrow 2Cr^{3+}(aq) + 3MnO_2(s) + H_2O(\ell)$

5.16 Assign oxidation numbers to each element in the following equations and identify the oxidizing and reducing agents:

a. $2Cu(s) + O_2(g) \rightarrow 2CuO(s)$
b. $Cl_2(aq) + 2KI(aq) \rightarrow 2KCl(aq) + I_2(aq)$
c. $3MnO_2(s) + 4Al(s) \rightarrow 2Al_2O_3(s) + 3Mn(s)$
d. $2H^+(aq) + 3SO_3^{2-}(aq) + 2NO_3^-(aq) \rightarrow 2NO(g) + H_2O(\ell) + 3SO_4^{2-}(aq)$
e. $Mg(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + H_2(g)$
f. $4NO_2(g) + O_2(g) \rightarrow 2N_2O_5(g)$

5.17 The overall reaction for photosynthesis is

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

Is this a redox reaction? If so, identify the reducing and oxidizing agents.

5.18 Aluminum metal reacts rapidly with highly basic solutions to liberate hydrogen gas and a large amount of heat. This reaction is utilized in a popular solid drain cleaner that is composed primarily of lye (sodium hydroxide) and aluminum granules. When wet, the mixture reacts as follows:

$$6NaOH(aq) + 2Al(s) \rightarrow 3H_2(g) + 2Na_3AlO_3(aq) + \text{heat}$$

The liberated H_2 provides agitation that, together with the heat, breaks the drain stoppage loose. What are the oxidizing and reducing agents in the reaction?

5.19 To feed the billions of people on this planet, farmers rely on nitrogen fertilizers produced through the Haber process. This process produces ammonia from elemental nitrogen and hydrogen. The ammonia is then further processed. The equation for the reaction is:

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$$

Identify the oxidizing and reducing agents in the Haber process.

Decomposition, Combination, and Replacement Reactions (Sections 5.4–5.6)

5.20 Classify each of the reactions represented by the following equations, first as a redox or nonredox reaction. Then further classify each redox reaction as a decomposition, single-replacement, or combination reaction, and each nonredox reaction as a decomposition, double-replacement, or combination reaction.

a. $K_2CO_3(s) \rightarrow K_2O(s) + CO_2(g)$
b. $Ca(s) + 2H_2O(\ell) \rightarrow Ca(OH)_2(s) + H_2(g)$
c. $BaCl_2(aq) + H_2SO_4(aq) \rightarrow BaSO_4(s) + 2HCl(aq)$
d. $SO_2(g) + H_2O(\ell) \rightarrow H_2SO_3(aq)$
e. $2NO(g) + O_2(g) \rightarrow 2NO_2(g)$
f. $2Zn(s) + O_2(g) \rightarrow 2ZnO(s)$

5.21 Classify each of the reactions represented by the following equations, first as a redox or nonredox reaction. Then further classify each redox reaction as a decomposition, single-replacement, or combination reaction, and each nonredox reaction as a decomposition, double-replacement, or combination reaction:

a. $N_2O_5(g) + H_2O(\ell) \rightarrow 2HNO_3(aq)$
b. $Cr_2O_3(s) + 2Al(s) \rightarrow 2Cr(s) + Al_2O_3(s)$
c. $CaO(s) + SiO_2(s) \rightarrow CaSiO_3(s)$
d. $H_2CO_3(aq) \rightarrow CO_2(g) + H_2O(\ell)$
e. $PbCO_3(s) \rightarrow PbO(s) + CO_2(g)$
f. $Zn(s) + Cl_2(g) \rightarrow ZnCl_2(s)$

5.22 Cooking fires are the number one cause of home fires and home fire injuries. Baking soda ($NaHCO_3$) can serve as an emergency fire extinguisher for grease fires in the kitchen. When heated, it liberates CO_2, which smothers the fire. The equation for the reaction is

$$2NaHCO_3(s) \xrightarrow{\text{Heat}} Na_2CO_3(s) + H_2O(g) + CO_2(g)$$

Classify the reaction into the categories used in Exercises 5.20 and 5.21.

5.23 Baking soda may serve as a source of CO_2 in bread dough. It causes the dough to rise. The CO_2 is released when $NaHCO_3$ reacts with an acidic substance:

$$NaHCO_3(aq) + H^+(aq) \rightarrow Na^+(aq) + H_2O(\ell) + CO_2(g)$$

Classify the reaction as redox or nonredox.

5.24 Since the 1800s, natural gas has replaced coal as a heating and electrical-power generating source. This change has reduced the amount of air pollution emissions linked to lung diseases. Today many homes are heated by the energy released when natural gas (represented by CH_4) reacts with oxygen. The equation for the reaction is

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$$

Classify the reaction as redox or nonredox.

5.25 Hydrogen peroxide solutions are used as an antiseptic to treat wounds. Hydrogen peroxide will react with and liberate oxygen gas. In commercial solutions, the reaction is prevented to a larger degree by the addition of an inhibitor. The equation for the oxygen-liberating reaction is

$$2H_2O_2(aq) \rightarrow 2H_2O(\ell) + O_2(g)$$

Classify the reaction as redox or nonredox.

5.26 Chlorine, used to treat drinking water, undergoes the reaction in water represented by the following equation:

$$Cl_2(aq) + H_2O(\ell) \rightarrow HOCl(aq) + HCl(aq)$$

Classify the reaction as redox or nonredox.

5.27 Triple superphosphate, an ingredient of some fertilizers, is prepared by reacting rock phosphate (calcium phosphate) and phosphoric acid. The equation for the reaction is

$$Ca_3(PO_4)_2(s) + 4H_3PO_4(aq) \rightarrow 3Ca(H_2PO_4)_2(s)$$

Classify the reaction into the categories used in Exercises 5.20 and 5.21.

Ionic Equations (Section 5.7)

5.28 Consider all of the following ionic compounds to be water soluble, and write the formulas of the ions that would be formed if the compounds were dissolved in water. **Table 4.7** will be helpful.

a. $LiNO_3$
b. Na_2HPO_4
c. $Ca(ClO_3)_2$
d. KOH
e. $MgBr_2$
f. $(NH_4)_2SO_4$

5.29 Consider all of the following ionic compounds to be water soluble, and write the formulas of the ions that would be formed if the compounds were dissolved in water. **Table 4.7** will be helpful.

a. Na_2SO_4
b. $CaCl_2$
c. $(NH_4)_3PO_4$
d. $NaOH$
e. KNO_3
f. $NaMnO_4$

5.30* Reactions represented by the following equations take place in water solutions. Write each molecular equation in total ionic form, then identify spectator ions and write the equations in net ionic form. Solids that do not dissolve are designated by (s), gases that do not dissolve are designated by (g), and substances that dissolve but do not dissociate appear in blue.

a. $SO_2(aq) + H_2O(\ell) \rightarrow H_2SO_3(aq)$
b. $CuSO_4(aq) + Zn(s) \rightarrow Cu(s) + ZnSO_4(aq)$
c. $2KBr(aq) + 2H_2SO_4(aq) \rightarrow Br_2(aq) + SO_2(aq) + K_2SO_4(aq) + 2H_2O(\ell)$
d. $AgNO_3(aq) + NaOH(aq) \rightarrow AgOH(s) + NaNO_3(aq)$
e. $BaCO_3(s) + 2HNO_3(aq) \rightarrow Ba(NO_3)_2(aq) + CO_2(g) + H_2O(\ell)$
f. $N_2O_5(aq) + H_2O(\ell) \rightarrow 2HNO_3(aq)$

5.31* Reactions represented by the following equations take place in water solutions. Write each molecular equation in total ionic form, then identify spectator ions and write the equations in net ionic form. Solids that do not dissolve are designated by (s), gases that do not dissolve are designated by (g), and substances that dissolve but do not dissociate appear in blue.

a. $H_2O(\ell) + Na_2SO_3(aq) + SO_2(aq) \rightarrow 2NaHSO_3(aq)$
b. $3Cu(s) + 8HNO_3(aq) \rightarrow 3Cu(NO_3)_2(aq) + 2NO(g) + 4H_2O(\ell)$
c. $2HCl(aq) + CaO(s) \rightarrow CaCl_2(aq) + H_2O(\ell)$
d. $CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + CO_2(aq) + H_2O(\ell)$
e. $MnO_2(s) + 4HCl(aq) \rightarrow MnCl_2(aq) + Cl_2(aq) + 2H_2O(\ell)$
f. $2AgNO_3(aq) + Cu(s) \rightarrow Cu(NO_3)_2(aq) + 2Ag(s)$

5.32* The following molecular equations all represent neutralization reactions of acids and bases. These reactions will be discussed further in Chapter 9. Write each equation in total ionic form, identify the spectator ions, then write the net ionic equation. Water is the only substance that does not dissociate. What do you notice about all the net ionic equations?

a. $HNO_3(aq) + KOH(aq) \rightarrow KNO_3(aq) + H_2O(\ell)$
b. $H_3PO_4(aq) + 3NH_4OH(aq) \rightarrow (NH_4)_3PO_4(aq) + 3H_2O(\ell)$
c. $HI(aq) + NaOH(aq) \rightarrow NaI(aq) + H_2O(\ell)$

5.33* The following molecular equations all represent neutralization reactions of acids and bases. These reactions will be discussed further in Chapter 9. Write each equation in total ionic form, identify the spectator ions, then write the net ionic equation. Water is the only substance that does not dissociate. What do you notice about all the net ionic equations?

a. $HCl(aq) + LiOH(aq) \rightarrow LiCl(aq) + H_2O(\ell)$
b. $H_3PO_4(aq) + 3KOH(aq) \rightarrow K_3PO_4(aq) + 3H_2O(\ell)$
c. $H_2SO_4(aq) + 2NH_4OH(aq) \rightarrow (NH_4)_2SO_4(aq) + 2H_2O(\ell)$

Energy and Reactions (Section 5.8)

5.34 In addition to emergency cold packs, emergency hot packs are available that heat up when water is mixed with a solid. Is the process that takes place in such packs exothermic or endothermic? Explain.

5.35 Refrigeration systems ensure that healthy fresh/frozen food is available to many billions of people worldwide. In refrigeration systems, the area to be cooled has pipes running through it. Inside the pipes, a liquid evaporates and becomes a gas. Is the evaporation process exothermic or endothermic? Explain.

5.36 To decrease the chance of food poisoning, an individual wants to keep some food cold in a portable picnic cooler. A piece of ice is put into the cooler, but it is wrapped in a thick insulating blanket to slow its melting. Comment on the effectiveness of the cooler in terms of the direction of heat movement inside it.

5.37 The human body cools itself by the evaporation of perspiration. Is the evaporation process endothermic or exothermic? Explain.

The Mole and Chemical Equations (Section 5.9)

5.38 For the reactions represented by the following equations, write statements equivalent to Statements 2, 3, and 4 given in **Section 5.9**.

a. $S(s) + O_2(g) \rightarrow SO_2(g)$

b. $Sr(s) + 2H_2O(\ell) \rightarrow Sr(OH)_2(s) + H_2(g)$

c. $2H_2S(g) + 3O_2(g) \rightarrow 2H_2O(g) + 2SO_2(g)$

d. $4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(g)$

e. $CaO(s) + 3C(s) \rightarrow CaC_2(s) + CO(g)$

5.39 For the reactions represented by the following equations, write statements equivalent to Statements 2, 3, and 4 given in **Section 5.9**.

a. $2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$

b. $4HCl(g) + O_2(g) \rightarrow 2Cl_2(g) + 2H_2O(g)$

c. $Fe_2O_3(s) + 3C(s) \rightarrow 2Fe(s) + 3CO(g)$

d. $2H_2O_2(aq) \rightarrow 2H_2O(\ell) + O_2(g)$

e. $2C_3H_6(g) + 9O_2(g) \rightarrow 6CO_2(g) + 6H_2O(g)$

5.40 For the following equation, write statements equivalent to Statements 2, 3, and 4 given in **Section 5.9**. Then write at least six factors (including numbers and units) that could be used to solve problems by the factor-unit method.

$$2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$$

5.41 Calculate the number of grams of SO_2 that must react to produce 350.0 g of SO_3. Use the statements written in Exercise 5.40 and express your answer using the correct number of significant figures.

5.42 Calculate the mass of limestone ($CaCO_3$) that must be decomposed to produce 500.0 g of lime (CaO). The equation for the reaction is

$$CaCO_3(s) \rightarrow CaO(s) + CO_2(g)$$

5.43 Calculate the number of moles of CO_2 generated by the reaction of Exercise 5.42 when 500.0 g of CaO is produced.

5.44 Calculate the number of grams of bromine (Br_2) needed to react exactly with 50.1 g of aluminum (Al). The equation for the reaction is

$$2Al(s) + 3Br_2(\ell) \rightarrow 2AlBr_3(s)$$

5.45 Calculate the number of moles of $AlBr_3$ produced by the process of Exercise 5.44.

5.46 How many grams of $AlBr_3$ are produced by the process in Exercise 5.44?

5.47* Given the following equation for the reaction used to clean tarnish from silver:

$$3Ag_2S(s) + 2Al(s) \rightarrow 6Ag(s) + Al_2S_3(s)$$

a. How many grams of aluminum would need to react to remove 0.250 g of Ag_2S tarnish?

b. How many moles of Al_2S_3 would be produced by the reaction described in (a)?

5.48 Pure titanium metal is produced by reacting titanium(IV) chloride with magnesium metal. The equation for the reaction is

$$TiCl_4(s) + 2Mg(s) \rightarrow Ti(s) + 2MgCl_2(s)$$

How many grams of Mg would be needed to produce 1.00 kg of pure titanium?

5.49 An important metabolic process of the body is the oxidation of glucose to water and carbon dioxide. The equation for the reaction is

$$C_6H_{12}O_6(aq) + 6O_2(aq) \rightarrow 6CO_2(aq) + 6H_2O(\ell)$$

a. What mass of water in grams is produced when the body oxidizes 1.00 mol of glucose?

b. How many grams of oxygen are needed to oxidize 1.00 mol of glucose?

5.50 Caproic acid is oxidized in the body as follows:

$$C_6H_{12}O_2(aq) + 8O_2(aq) \rightarrow 6CO_2(aq) + 6H_2O(\ell)$$

How many grams of oxygen are needed to oxidize 1.00 mol of caproic acid?

The Limiting Reactant (Section 5.10)

5.51* A sample of 4.00 g of methane (CH_4) is mixed with 15.0 g of chlorine (Cl_2).

a. Determine which is the limiting reactant according to the following equation:

$$CH_4(g) + 4Cl_2(g) \rightarrow CCl_4(\ell) + 4HCl(g)$$

b. What is the maximum mass of CCl_4 that can be formed?

5.52* Nitrogen and oxygen react as follows:

$$N_2(g) + 2O_2(g) \rightarrow 2NO_2(g)$$

Suppose 1.25 mol of N_2 and 50.0 g of O_2 are mixed together.

a. Which one is the limiting reactant?

b. What is the maximum mass in grams of NO_2 that can be produced from the mixture?

5.53* Suppose you want to use acetylene (C_2H_2) as a fuel. You have a cylinder that contains 5.00×10^2 g of C_2H_2 and a cylinder that contains 2.00×10^3 g of oxygen (O_2). Do you have enough oxygen to burn all the acetylene? The equation for the reaction is

$$2C_2H_2(g) + 5O_2(g) \rightarrow 4CO_2(g) + 2H_2O(g)$$

5.54* Ammonia, carbon dioxide, and water vapor react to form ammonium bicarbonate as follows:

$$NH_3(aq) + CO_2(aq) + H_2O(\ell) \rightarrow NH_4HCO_3(aq)$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Suppose 50.0 g of NH_3, 80.0 g of CO_2, and 2.00 mol of H_2O are reacted. What is the maximum number of grams of NH_4HCO_3 that can be produced?

5.55 Chromium metal (Cr) can be prepared by reacting the oxide with aluminum. The equation for the reaction is

$$Cr_2O_3(s) + 2Al(s) \rightarrow 2Cr(s) + Al_2O_3(s)$$

What three substances will be found in the final mixture if 150 g of Cr_2O_3 and 150 g of Al are reacted?

Reaction Yields (Section 5.11)

5.56 The actual yield of a reaction was 11.74 g of product, while the calculated theoretical yield was 16.09 g. What was the percentage yield?

5.57 A product weighing 14.37 g was isolated from a reaction. The amount of product possible according to a calculation was 17.55 g. What was the percentage yield?

5.58 For a combination reaction, it was calculated that 7.59 g of *A* would exactly react with 4.88 g of *B*. These amounts were reacted, and 9.04 g of product was isolated. What was the percentage yield of the reaction?

5.59 A sample of calcium metal with a mass of 2.00 g was reacted with excess oxygen. The following equation represents the reaction that took place:

$$2Ca(s) + O_2(g) \rightarrow 2CaO(s)$$

The isolated product (CaO) weighed 2.26 g. What was the percentage yield of the reaction?

5.60 Upon heating, mercury(II) oxide undergoes a decomposition reaction:

$$2HgO(s) \rightarrow 2Hg(\ell) + O_2(g)$$

A sample of HgO weighing 7.22 g was heated. The collected mercury weighed 5.95 g. What was the percentage yield of the reaction?

Additional Exercises

5.61 Would you expect argon, Ar, to be involved in a redox reaction? Explain your reasoning.

5.62 Rewrite the following word equation using chemical formulas. Balance the equation and write the balanced equation in net ionic form:

barium chloride (aq) + sodium sulfate (aq) →
sodium chloride (aq) + barium sulfate (s)

5.63 The element with an electron configuration of $1s^22s^22p^63s^1$ undergoes a combination reaction with the element that has 15 protons in its nucleus. Assume the product of the reaction consists of simple ions, and write a balanced chemical equation for the reaction.

5.64 Assuming a 100% reaction yield, it was calculated that 6.983 g of naturally occurring elemental iron would be needed to react with another element to form 18.149 g of product. If iron composed only of the iron-60 isotope was used to form the product, how many grams of iron-60 would be required?

5.65 The decomposition of a sample of a compound produced 1.20×10^{24} atoms of nitrogen and 80.0 grams of oxygen atoms. What was the formula of the sample that was decomposed? What is the correct name of the decomposed sample?

Chemistry for Thought

5.66 In experiments where students prepare compounds by precipitation from water solutions, they often report yields of dry product greater than 100%. Propose an explanation for this.

5.67 Refer to **Figure 5.5** and follow the instructions. Then explain how the concept of limiting reactant is used to extinguish a fire.

5.68 Refer to **Figure 5.7** and answer the question. Suggest another material that might provide the enzyme catalyst.

5.69 What do the observations of **Figure 5.13** indicate to you about the abilities of the following solids to dissolve in water: NaCl, $AgNO_3$, and AgCl? What would you expect to observe if you put a few grams of solid AgCl into a test tube containing 3 mL of water and shook the mixture? What would you expect to observe if you repeated this experiment but used a few grams of $NaNO_3$ instead of AgCl?

5.70 The concentration of alcohol (CH_3CH_2OH) in the breath of an individual who has been drinking is measured by an instrument called a Breathalyzer. The breath sample is passed through a solution that contains the orange-colored $Cr_2O_7{}^{2-}$ ion. The equation for the net ionic redox reaction that occurs is:

$$2Cr_2O_7{}^{2-}(aq) + 3CH_3CH_2OH(aq) + 16H^+(aq) \rightarrow 4Cr^{3+}(aq) + 3CH_3COOH(aq) + 11H_2O(\ell)$$

The Cr^{3+} ion has a pale violet color in solution. Explain how color changes in the solution could be used to indicate the amount of alcohol in the breath sample.

5.71 Certain vegetables and fruits, such as potatoes and apples, darken quickly when sliced. Submerging the slices in water slows this process. Explain.

5.72 In an ordinary flashlight battery, an oxidation reaction and a reduction reaction take place at different locations to produce an electrical current that consists of electrons. In one of the reactions, the zinc container of the battery slowly dissolves as it is converted into zinc ions. Is this the oxidation or the reduction reaction? Is this reaction the source of electrons, or are electrons used to carry out the reaction? Explain your answers with a reaction equation.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

6 The States of Matter

Евгений Харитонов/iStock/Getty Images

Environmental Career Focus

FIELD CHEMIST

This job isn't for everyone. I work with landfills and water-treatment plants. You know, waste. ALL kinds of human waste. Somebody's got to do it. I'm proud of my work. Our family business has changed over the years with increased regulation and new technologies. You used to be able to learn on the job, but now you need a degree. Not only do you need to know about the chemicals you handle and monitor, but you also need technical writing skills for the local and state government reports.

It's important to know what you're doing. Waste generates gases, which can cause fires and even explosions, not to mention contamination and disease from solid waste. The chemicals used to mitigate contaminants, like chlorine, can be toxic, so you have to be very careful.

Some employees work in the field like me, some work in the labs, and some handle the paperwork. Our labs certify that sites meet EPA guidelines. You have to be accurate. We're dealing with people's businesses—their livelihoods—the stakes are high. If we certify a community's water as safe, or confirm that a city is meeting clean-water standards for streams near landfills, that's important. Really important.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Do calculations based on the property of density. **(Section 6.1)**
2. Demonstrate an understanding of the kinetic molecular theory of matter. **(Section 6.2)**
3. Use the kinetic molecular theory to explain and compare the properties of matter in different states. **(Sections 6.3–6.5)**
4. Do calculations to convert pressure and temperature values into various units. **(Section 6.6)**
5. Do calculations based on Boyle's law, Charles's law, and the combined gas law. **(Section 6.7)**
6. Do calculations based on the ideal gas law. **(Section 6.8)**
7. Do calculations based on Dalton's law. **(Section 6.9)**
8. Do calculations based on Graham's law. **(Section 6.10)**

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

9 Classify changes in state as exothermic or endothermic. **(Section 6.11)**

10 Demonstrate an understanding of the concepts of vapor pressure and evaporation. **(Section 6.12)**

11 Demonstrate an understanding of the process of boiling and the concept of boiling point. (**Section 6.13)**

12 Demonstrate an understanding of the processes of sublimation and melting. **(Section 6.14)**

13 Do calculations based on energy changes that accompany heating, cooling, or changing the state of a substance. **(Section 6.15)**

IF YOU LIVE in an area that has cold winters, you have probably seen water in the three different forms used to categorize the states in which matter occurs. On a cold day, you can usually find solid water (ice) floating in a pool of cold liquid water, and at the same time you can see a small cloud of tiny water droplets that forms when gaseous water condenses as you exhale into the cold air.

Most matter is not as easily observed in all three states as the water in the preceding example. In fact, most matter is classified as a solid, a liquid, or a gas on the basis of the form in which it is commonly observed. However, according to **Section 4.11**, the state of a substance depends on temperature. You will see in this chapter that the state also depends on pressure. Therefore, when a substance is classified as a solid, a liquid, or a gas, we are usually simply stating its form under normal atmospheric pressure and at a temperature near 25°C. **Figure 6.1** gives the states of the elements under those conditions.

In this chapter, we will study the characteristics of the common states of matter, along with a theory that relates these states to molecular behavior. We will also investigate the energy relationships that accompany changes of state.

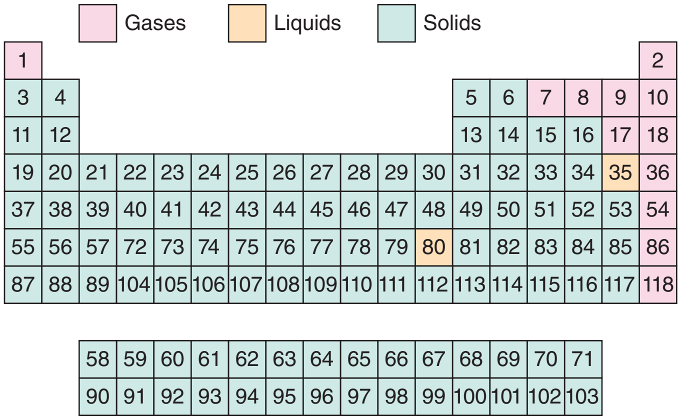

Gases
Liquids
Solids
1 2
3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18
19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36
37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54
55 56 57 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86
87 88 89 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118
58 59 60 61 62 63 64 65 66 67 68 69 70 71
90 91 92 93 94 95 96 97 98 99 100 101 102 103

FIGURE 6.1 The common states of the elements at normal atmospheric pressure and 25°C.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

6.1 Observed Properties of Matter

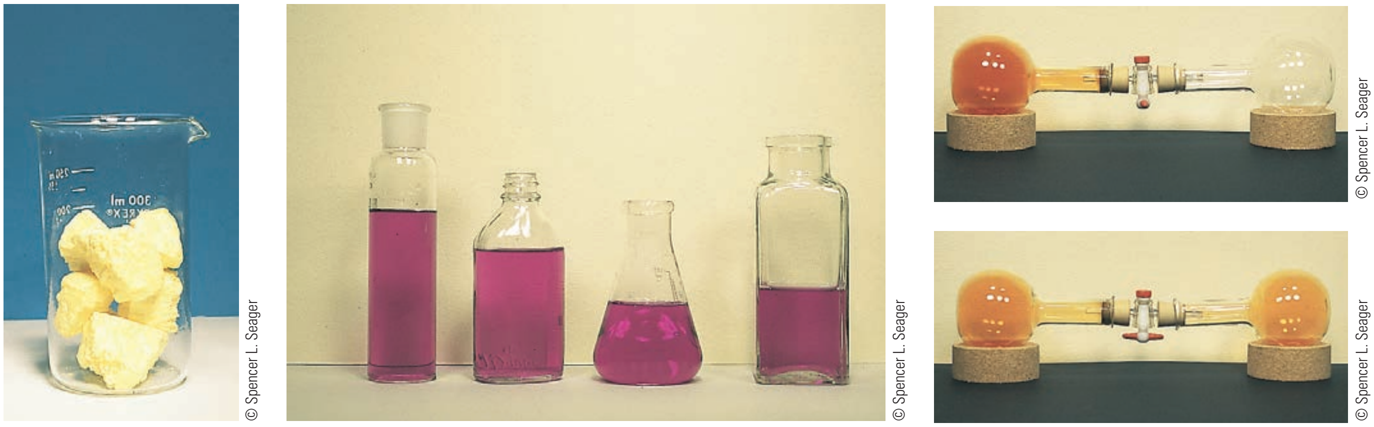
Learning Objective 1 Do calculations based on the property of density.

Solids, liquids, and gases can easily be recognized and distinguished by differences in physical properties. Four properties that can be used are density, shape, compressibility, and thermal expansion.

Density was defined in **Section 1.11** as the mass of a sample of matter divided by the volume of the same sample. A failure to remember this is the basis for the wrong answers given to the children's riddle, "Which is heavier, a pound of lead or a pound of feathers?" Of course, they weigh the same, but many people say lead is heavier because they think in terms of samples having the same volume. Of course, if you have lead and feather samples of the same volume, the lead sample will be much heavier because its density is much greater.

shape Shape depends on the physical state of matter.

The **shape** of matter is sometimes independent of a container (for solids), or it may be related to the shape of the container (for liquids and gases). In the case of liquids, the shape depends on the extent to which the container is filled. Gases always fill the container completely (see **Figure 6.2**).



© Spencer L. Seager

a Solids have a shape and volume that does not depend on the container.

b Liquids take the shape of the part of the container they fill. Each sample above has the same volume.

c Gases completely fill and take the shape of their container. When the valve separating the two parts of the container is opened, the gas fills the entire container volume (bottom photo).

FIGURE 6.2 Characteristics of the states of matter.

compressibility The change in volume of a sample resulting from a pressure change acting on the sample.

thermal expansion The change in volume of a sample resulting from a change in temperature of the sample.

Compressibility, the change in volume resulting from a pressure change, is quite high for gases. Compressibility allows a lot of gas to be squeezed into a small volume if the gas is put under sufficient pressure—think of automobile tires, or a tank of compressed helium used to fill toy balloons.

Thermal expansion, the change in volume resulting from temperature changes, is a property used in liquid-in-glass thermometers. As the temperature of the liquid increases, the liquid expands and fills more of the fine capillary tube on which the temperature scale is engraved. You see the liquid move up the tube and know the temperature is increasing.

These four properties are compared for the three states (see **Figure 6.3**) of matter in **Table 6.1**.

TABLE 6.1 Physical Properties of Solids, Liquids, and Gases

	State		
Property	**Solid**	**Liquid**	**Gas**
Density	High	High—usually lower than that of corresponding solid	Low
Shape	Definite	Indefinite—takes shape of container to the extent it is filled	Indefinite—takes shape of container it fills
Compressibility	Small	Small—usually greater than that of corresponding solid	Large
Thermal expansion	Very small	Small	Moderate

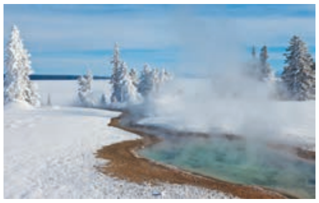

Ralph Lee Hopkins/National Geographic Image Collection/Getty Images

FIGURE 6.3 This winter scene at Yellowstone National Park shows water in all three forms (solid, liquid, and gaseous vapor) simultaneously.

Example 6.1 Calculating Densities

Samples of plumber's solder, rubbing alcohol, and air are collected. The volume and mass of each sample are determined at 20°C as follows: solder—volume = 28.6 mL, mass = 268.8 g; alcohol—volume = 100.0 mL, mass = 78.5 g; air—volume = 500.0 mL, mass = 0.602 g. Calculate the density of each substance in grams per milliliter.

Solution

The density (d) is obtained by using key equation 1.9; divide the sample mass (in grams) by the sample volume (in milliliters):

$$\text{solder:} \qquad d = \frac{268.8}{28.6\text{ mL}} = 9.40\text{ g/mL}$$

$$\text{alcohol:} \qquad d = \frac{78.5\text{ g}}{100.0\text{ mL}} = 0.785\text{ g/mL}$$

$$\text{air:} \qquad d = \frac{0.602\text{ g}}{500.0\text{ mL}} = 0.00120\text{ g/mL}$$

The calculated densities follow the pattern given in **Table 6.1**.

✔ LEARNING CHECK 6.1 Samples of copper, glycerin, and helium are collected and weighed at 20°C. The results are as follows: copper—volume = 12.8 mL, mass = 114.2 g; glycerin—volume = 50.0 mL, mass = 63.0 g; helium—volume = 1500 mL, mass = 0.286 g.

a. Calculate the density of each sample at 20°C.
b. Describe qualitatively (increase, decrease, little change, no change, etc.) what happens to the following properties for each sample when the pressure on the sample is doubled: sample volume, sample mass, sample density (see **Table 6.1**).

The density calculations done in Example 6.1 used Equation 1.9, which is repeated here:

$$d = \frac{m}{V}$$

Remember, in this equation d is density, m is mass, and V is volume. This useful equation can be rearranged so that any one quantity in it can be calculated if the other two are known.

Example 6.2 Calculating Volumes Using Densities

Rubbing alcohol is used topically to prevent bacterial skin infections from minor cuts or scrapes.

The sample of rubbing alcohol used in Example 6.1 is heated to 50°C. The density of the sample is found to decrease to a value of 0.762 g/mL. What is the volume of the sample at 50°C?

Solution

It is assumed that no alcohol is lost by evaporation, so the sample mass has the same value of 78.5 g it had in Example 6.1. Equation 1.9 is rearranged and solved for volume:

$$V = \frac{m}{d} \tag{6.1}$$

The new volume is

$$V = \frac{m}{d} = \frac{78.5 \cancel{\text{g}}}{0.762 \cancel{\text{g}}/\text{mL}} = 103 \text{ mL}$$

Thus, the heating causes the liquid to expand from a volume of 100 mL to 103 mL.

✔ **LEARNING CHECK 6.2** Calculate the mass in grams of a 1200 mL air sample at a temperature where the air has a density of 1.18×10^{-3} g/mL. *Note:* Equation 6.1 can be rearranged to $m = d \times V$.

6.2 The Kinetic Molecular Theory of Matter

Learning Objective 2 Demonstrate an understanding of the kinetic molecular theory of matter.

The long title of this section is the name scientists have given to a model or theory used to explain the behavior of matter in its various states. Some theories, including this one, are based on a group of generalizations or postulates. This useful practice makes it possible to study and understand each postulate individually, instead of the entire theory.

The postulates of the kinetic molecular theory are:

1. Matter is composed of tiny particles called molecules.
2. The particles are in constant motion and therefore possess kinetic energy.
3. The particles possess potential energy as a result of attracting or repelling each other.
4. The average particle speed increases as the temperature increases.
5. The particles transfer energy from one to another during collisions in which no net energy is lost from the system.

Volker Meyer/Pexels

FIGURE 6.4 Kinetic energy is associated with mass and speed. A skier in motion possesses kinetic energy.

kinetic energy The energy a particle has as a result of its motion. Mathematically, it is K.E. = $\frac{1}{2}mv^2$.

These postulates contain two new terms, kinetic energy and potential energy. **Kinetic energy** is the energy a particle has as a result of its motion. Mathematically, kinetic energy is calculated as

$$\text{K.E.} = \frac{1}{2}mv^2 \tag{6.2}$$

where m is the particle mass and v is its velocity (see **Figure 6.4**). Thus, if two particles of different mass are moving at the same velocity, the heavier particle will possess more kinetic energy than the other particle. Similarly, the faster moving of two particles with equal masses will have more kinetic energy.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 6.3 Calculating Kinetic Energies

Calculate the kinetic energy of two particles with masses of 2.00 g and 3.00 g if they are both moving at a velocity of 15.0 cm/s.

Solution

The kinetic energy of the 2.00 g particle is

$$\text{K.E.} = \frac{1}{2}(2.00\text{ g})\left(15.0\,\frac{\text{cm}}{\text{s}}\right)^2 = 225\,\frac{\text{g cm}^2}{\text{s}^2}$$

The kinetic energy of the 3.00 g particle is

$$\text{K.E.} = \frac{1}{2}(3.00\text{ g})\left(15.0\,\frac{\text{cm}}{\text{s}}\right)^2 = 337.5\,\frac{\text{g cm}^2}{\text{s}^2}$$

Rounding gives 338 g cm^2/s^2; thus, the more massive particle has more kinetic energy.

✔ **LEARNING CHECK 6.3** Calculate the kinetic energy of two 3.00 g particles if one has a velocity of 10.0 cm/s and the other has a velocity of 20.0 cm/s.

potential energy The energy a particle has as a result of attractive or repulsive forces acting on it.

cohesive forces The attractive force between particles; they are associated with potential energy.

disruptive forces The force resulting from particle motion; they are associated with kinetic energy.

Potential energy results from attractions or repulsions of particles. A number of these interactions are familiar, such as the gravitational attraction of Earth and the behavior of the poles of two magnets brought near each other. In each of these examples, the size of the force and the potential energy depend on the separation distance (see **Figure 6.5**). The same behavior is found for the potential energy of atomic-sized particles. The potential energy of attraction increases as separation distance increases, whereas the potential energy of repulsion decreases with increasing separation.

The kinetic molecular theory provides reasonable explanations for many of the observed properties of matter. An important factor in these explanations is the relative influence of cohesive forces and disruptive forces. **Cohesive forces** are the attractive forces associated with potential energy, and **disruptive forces** result from particle motion (kinetic energy). Disruptive forces tend to scatter particles and make them independent of each other; cohesive forces have the opposite effect. Thus, the state of a substance depends on the relative strengths of the cohesive forces that hold the particles together and the disruptive forces tending to separate them. Cohesive forces are essentially temperature-independent because they involve interparticle attractions of the type described in Chapter 4. Disruptive forces increase with temperature because they arise from particle motion, which increases with temperature (Postulate 4). This explains why temperature plays such an important role in determining the state in which matter is found.

Cavan Images/Getty Images

FIGURE 6.5 Potential energy is attributed to mass and position. A skier at the top of a hill possesses potential energy.

6.3 The Solid State

Learning Objective 3 Use the kinetic molecular theory to explain and compare the properties of matter in different states.

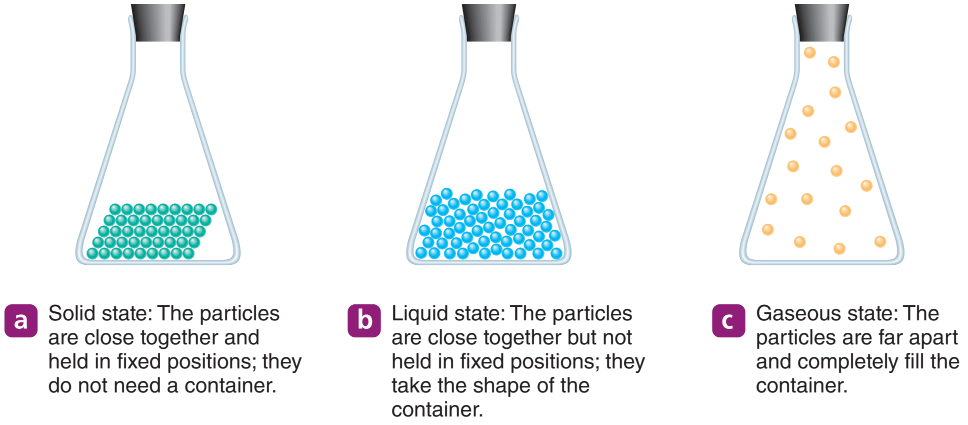
In the solid state, the cohesive forces are stronger than the disruptive forces (see **Figure 6.6A**). Each particle of a crystalline solid occupies a fixed position in the crystal lattice (see **Section 4.11**). Disruptive kinetic energy causes the particles to vibrate about their fixed positions, but the strong cohesive forces prevent the lattice from breaking down. The properties of solids in **Table 6.1** are explained by the kinetic theory as follows:

High density. The particles of solids are located as closely together as possible. Therefore, large numbers of particles are contained in a small volume, resulting in a high density.

Definite shape. The strong cohesive forces hold the particles of solids in essentially fixed positions, resulting in a definite shape.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

FIGURE 6.6 A kinetic molecular view of solids, liquids, and gases.


a Solid state: The particles are close together and held in fixed positions; they do not need a container.

b Liquid state: The particles are close together but not held in fixed positions; they take the shape of the container.

c Gaseous state: The particles are far apart and completely fill the container.

Small compressibility. Because there is very little space between particles of solids, increased pressure cannot push them closer together, and it will have little effect on the volume.

Very small thermal expansion. Increased temperature increases the vibrational motion of the particles and the disruptive forces acting on them. Each particle vibrates with an increased amplitude and "occupies" a slightly larger volume. However, there is only a slight expansion of the solid because the strong cohesive forces prevent this effect from becoming very large.

6.4 The Liquid State

Learning Objective 3 Use the kinetic molecular theory to explain and compare the properties of matter in different states.

Particles in the liquid state are randomly packed and relatively close to each other (see **Figure 6.6(b)**). They are in constant, random motion, sliding freely over one another, but without sufficient kinetic energy, it is not possible to separate them completely from each other. The liquid state is a situation in which cohesive forces dominate slightly. The characteristic properties of liquids are also explained by the kinetic theory:

High density. The particles of liquids are not widely separated; they essentially touch each other. There will, therefore, be a large number of particles per unit volume and a high density.

Indefinite shape. Although not completely independent of each other, the particles in a liquid are free to move over and around each other in a random manner, limited only by the container walls and the extent to which the container is filled.

Small compressibility. Because the particles in a liquid essentially touch each other, there is very little space between them. Therefore, increased pressure cannot squeeze the particles much more closely together.

Small thermal expansion. Most of the particle movement in a liquid is vibrational because the particles can move only a short distance before colliding with its neighbor. Therefore, the increased particle velocity that accompanies a temperature increase results only in increased vibration. The net effect is that the particles push away from each other a little more, thereby causing a slight volume increase in the liquid.

6.5 The Gaseous State

Learning Objective 3 Use the kinetic molecular theory to explain and compare the properties of matter in different states.

Disruptive forces completely overcome cohesive forces between particles in the gaseous or vapor state. As a result, the particles of a gas move essentially independently of one another in a totally random way (see **Figure 6.6(c)**). Under ordinary pressure, the particles

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

are relatively far apart except when they collide with each other. Between collisions with each other or with the container walls, gas particles travel in straight lines. The particle velocities and resultant collision frequencies are quite high for gases, as shown in **Table 6.2**.

TABLE 6.2 Some Numerical Data Related to the Gaseous State

Gas	Average Speed at 0°C	Average Distance Traveled between Collisions at 1 atm of Pressure	Number of Collisions of 1 Molecule in 1 s at 1 atm of Pressure
Hydrogen (H_2)	169,000 cm/s (3700 mi/h)	1.12×10^{-5} cm	1.60×10^{10}
Nitrogen (N_2)	45,400 cm/s (1015 mi/h)	0.60×10^{-5} cm	0.80×10^{10}
Carbon dioxide (CO_2)	36,300 cm/s (811 mi/h)	0.40×10^{-5} cm	0.95×10^{10}

The kinetic theory explanation of gaseous-state properties follows the same pattern seen earlier for solids and liquids:

Low density. The particles of a gas are widely separated. There are relatively few of them in a given volume, which means there is little mass per unit volume.

Indefinite shape. The forces of attraction between particles have been overcome by kinetic energy, and the particles are free to travel in all directions. The particles, therefore, completely fill the container and assume its inner shape.

Large compressibility. The gas particles are widely separated, so a gas sample is mostly empty space. When pressure is applied, the particles are easily pushed closer together, decreasing the amount of empty space and the gas volume, as shown by **Figure 6.7**.

Moderate thermal expansion. Gas particles move in straight lines except when they collide with each other or with container walls. An increase in temperature causes the particles to collide with more energy. Thus, they push each other away more strongly, and at constant pressure this causes the gas itself to occupy a significantly larger volume.

It must be understood that the size of the particles is not changed during expansion or compression of gases, liquids, or solids. The particles are merely moving farther apart or closer together, and the space between them is changed.

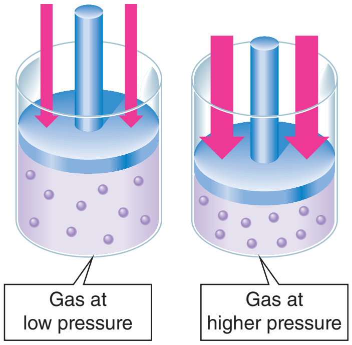


FIGURE 6.7 The compression of a gas.

6.6 The Gas Laws

Learning Objective 4 Do calculations to convert pressure and temperature values into various units.

The states of matter have not yet been discussed in quantitative terms. We have pointed out that solids, liquids, and gases expand when heated, but the amounts by which they expand have not been calculated. Such calculations for liquids and solids are beyond the intended scope of this text, but gases obey relatively simple quantitative relationships that were discovered during the 17th, 18th, and 19th centuries. These relationships, called **gas laws**, describe in mathematical terms the behavior of gases as they are mixed, subjected to pressure or temperature changes, or allowed to diffuse.

gas laws Mathematical relationships that describe the behavior of gases as they are mixed, subjected to pressure or temperature changes, or allowed to diffuse.

To use the gas laws, you must clearly understand the units used to express pressure, and you must utilize the Kelvin temperature scale introduced in **Section 1.6**. **Pressure** is defined as force per unit area. However, most of the units commonly used to express pressure reflect a relationship to barometric measurements of atmospheric pressure. The mercury barometer was invented by Italian physicist Evangelista Torricelli (1608–1647). Its essential components are shown in **Figure 6.8**. A glass tube, sealed at one end, is filled with mercury, stoppered, and inverted so that the stoppered end is under

pressure A force per unit area of surface on which the force acts. In measurements and calculations involving gases, it is often expressed in units related to measurements of atmospheric pressure.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

the surface of a pool of mercury. When the stopper is removed, the mercury in the tube falls until its weight is just balanced by the weight of air pressing on the mercury pool. The pressure of the atmosphere is then expressed in terms of the height of the supported mercury column.

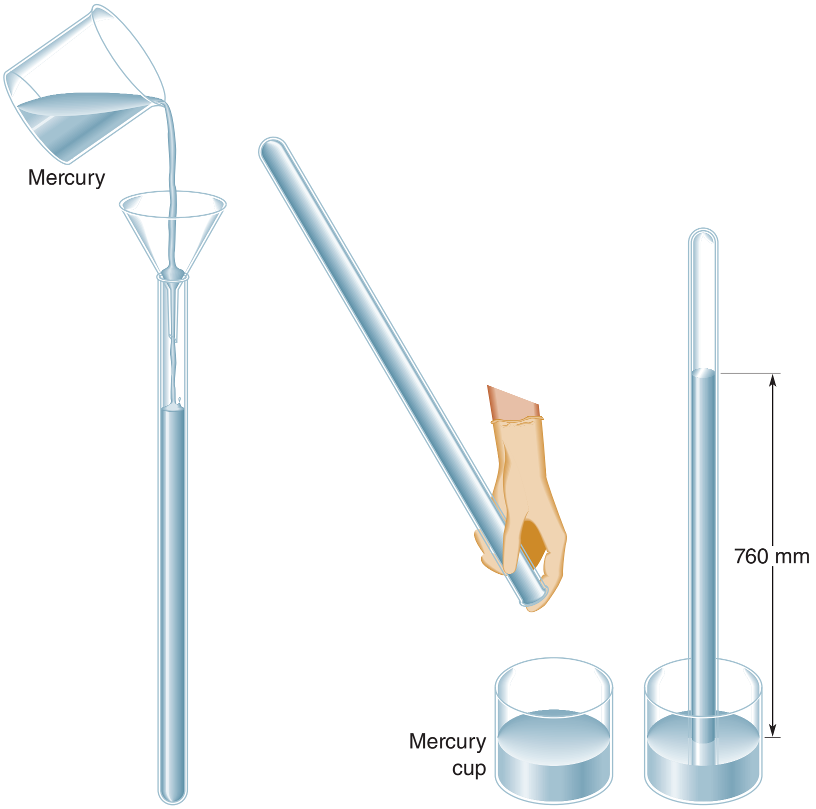


FIGURE 6.8 Setting up a simple mercury barometer. Standard atmospheric pressure is 760 mm of mercury.

Despite attempts to standardize measurement units, you will probably encounter a number of different units of pressure in your future studies and employment. Some of the more common are standard atmosphere (atm), torr, millimeters of mercury (mmHg), inches of mercury (in. Hg), pounds per square inch (psi), bar, and kilopascals (kPa). One **standard atmosphere** is the pressure needed to support a 760-mm column of mercury in a barometer tube, and 1 **torr** (named in honor of Torricelli) is the pressure needed to support a 1-mm column of mercury in a barometer tube. The relationships of the various units to the standard atmosphere are given in **Table 6.3**. Note that the values of 1 atm and 760 torr (or 760 mmHg) are exact numbers based on definitions and do not limit the number of significant figures in calculated numbers.

standard atmosphere The pressure needed to support a 760-mm column of mercury in a barometer tube.

torr The pressure needed to support a 1-mm column of mercury in a barometer tube.

TABLE 6.3 Units of Pressure

Unit	Relationship to One Standard Atmosphere	Typical Application
Atmosphere	—	Gas laws
Torr	760 torr = 1 atm	Gas laws
Millimeters of mercury	760 mmHg = 1 atm	Gas laws
Pounds per square inch	14.7 psi = 1 atm	Compressed gases
Bar	1.01 bar = 29.9 in. Hg = 1 atm	Meteorology
Kilopascal	101 kPa = 1 atm	Gas laws

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 6.4 Units of Gas Pressure

Hyperbaric therapy uses oxygen gas in treating decompression sickness, a hazard of scuba diving.

The gauge on a cylinder of compressed oxygen gas reads 1500. psi. Express this pressure in terms of (a) atm, (b) torr, and (c) mmHg.

Solution

We will use the factor-unit method of calculation from **Section 1.9**, and the necessary factors from **Table 6.3**.

a. It is seen from **Table 6.3** that 14.7 psi = 1 atm. Therefore, the known quantity, 1500. psi, is multiplied by the factor atm/psi in order to generate units of atm. The result is

$$1500.\ \cancel{\text{psi}}\left(\frac{1\ \text{atm}}{14.7\ \cancel{\text{psi}}}\right) = 1.0 \times 10^{2}\ \text{atm}$$

b. **Table 6.3** does not give a direct relationship between psi and torr. However, both psi and torr are related to atm. Therefore, the atm is used somewhat like a bridge between psi and torr:

$$(1500.\ \cancel{\text{psi}})\left(\frac{1\ \cancel{\text{atm}}}{14.7\ \cancel{\text{psi}}}\right)\left(\frac{760.\ \text{torr}}{1\ \cancel{\text{atm}}}\right) = 77{,}551\ \text{torr} = 7.8 \times 10^{4}\ \text{torr}$$

Note how the bridge term canceled out.

c. Because the torr and mmHg are identical, the problem is worked as it was in part b:

$$(1500.\ \cancel{\text{psi}})\left(\frac{1\ \cancel{\text{atm}}}{14.7\ \cancel{\text{psi}}}\right)\left(\frac{760.\ \text{mmHg}}{1\ \cancel{\text{atm}}}\right) = 7.8 \times 10^{4}\ \text{mmHg}$$

✔ **LEARNING CHECK 6.4** A barometer has a pressure reading of 670. torr. Convert this reading into (a) atm and (b) psi.

According to the kinetic molecular theory, a gas expands when it is heated at constant pressure, because the gaseous particles move faster at the higher temperature. It makes no difference to the particles what temperature scale is used to describe the heating. However, gas law calculations are based on the Kelvin temperature scale (**Section 1.6**) rather than the Celsius or Fahrenheit scales. The only apparent difference between the Kelvin and Celsius scales is the location of the zero reading (see **Figure 1.17**). It should be noted that a 0 reading on the Kelvin scale has a great deal of significance. It is the lowest possible temperature and is called **absolute zero**. It represents the temperature at which particles have no kinetic energy because all motion stops. The Kelvin and Celsius temperature scales have the same size degree, but the 0 of the Kelvin scale is 273 degrees below the freezing point of water, which is the 0 of the Celsius scale. Thus, a Celsius reading can be converted to a Kelvin reading simply by adding 273 (see **Figure 6.9**).

absolute zero The temperature at which all motion stops; a value of 0 on the Kelvin scale.

Example 6.5 Converting Temperature Values

Hospital use of the Kelvin temperature scale is convenient for recording very low temperatures of liquid helium (cooling of MRI magnets) and liquid nitrogen (cryosurgery).

Refer to **Figure 1.17** for the necessary conversion factors, and make the following temperature conversions (remember, Kelvin temperatures are expressed in kelvins, K):

a. 37°C (body temperature) to K   b. −50.°C to K   c. 400. K to °C

Solution

a. Celsius is converted to Kelvin by adding 273, K = °C + 273. Therefore,

$$\text{K} = 37°\text{C} + 273 = 310.\ \text{K (body temperature)}$$

Amelie-Benoist/BSIP SA/Alamy Stock Photo

FIGURE 6.9 The temperature of liquid nitrogen used in cryogenic surgery is between 63 K and 77 K.

HEALTH CONNECTIONS **6.1**

Get an Accurate Blood Pressure Reading

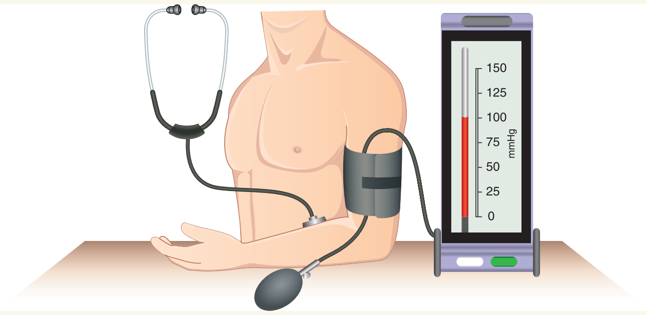
The measurement of blood pressure seems to be a very straightforward process. Stick your arm in a cuff for a few seconds, and read the two values that appear. However, blood pressure is a moving target, with a value that can vary from hour to hour or even minute to minute depending on a number of variables. Getting an accurate reading requires some knowledge of what these variables are.

Stress, body posture (sitting or standing), eating a meal, an exciting or a soothing music or video, and even the time of day can influence blood pressure. Because it changes so much, you are more likely to obtain a "normal" reading if you check blood pressure at home rather than have it taken in a doctor's office. The American Heart Association recommends this practice for individuals with high blood pressure or the risk of developing it.

To get an accurate blood pressure reading, you should become educated about factors that influence it. The following are six tips for getting the most accurate readings:

1. **Take your blood pressure readings at the same time each day.** Levels are usually lowest in the morning and increase through the day.
2. **Go to the bathroom.** A full bladder can raise systolic pressure by 10–15 mmHg. Diuretics (a common blood pressure medication) lower blood pressure by causing the kidneys to remove more sodium and water from the body: this helps to relax the blood vessel walls.
3. **Rest for 5 minutes before taking blood pressure readings.** Exertion can raise your blood pressure.
4. **Avoid exercise, tobacco, and caffeine for at least an hour before taking a reading.** All of these can make blood pressure spike temporarily.
5. **Use proper technique.** Feet should be flat on the floor, legs uncrossed, and cuff at heart level. These factors can each influence the systolic pressure by 2–10 mmHg.
6. **Put the cuff on bare skin.** Putting the cuff over clothes can increase the systolic pressure by 10–15 mmHg.

Know your numbers. Ask your doctor what range is ideal for you, and what reading should prompt an immediate call to the medical office. Contact your doctor if you have any unusual or persistent increases in your pressure.



A sphygmomanometer reports blood pressure as a ratio such as 100/80 (the higher, or systolic, blood pressure is shown here).

b. Again, 273 is added to the Celsius reading. However, in this case the Celsius reading is negative, so the addition must be done with the signs in mind. Therefore,

$$K = -50.°C + 273 = 223 \text{ K}$$

c. Because K = °C + 273, an algebraic rearrangement shows that °C = K − 273. Therefore,

$$°C = 400. \text{ K} - 273 = 127°C$$

✔ **LEARNING CHECK 6.5** Convert the following Celsius temperatures into kelvins, and the Kelvin (K) temperatures into degrees Celsius:
a. 27°C b. 0.°C c. 0.00 K d. 100. K

6.7 Pressure, Temperature, and Volume Relationships

Learning Objective 5 Do calculations based on Boyle's law, Charles's law, and the combined gas law.

Experimental investigations into the behavior of gases as they were subjected to changes in temperature and pressure led to several gas laws that could be expressed by simple mathematical equations. In 1662 Robert Boyle, an Irish chemist, reported his discovery of a relationship between the pressure and volume of a gas sample kept at constant temperature. This relationship, known as **Boyle's law**, is

$$P = \frac{k}{V} \tag{6.3}$$

or

$$PV = k \tag{6.4}$$

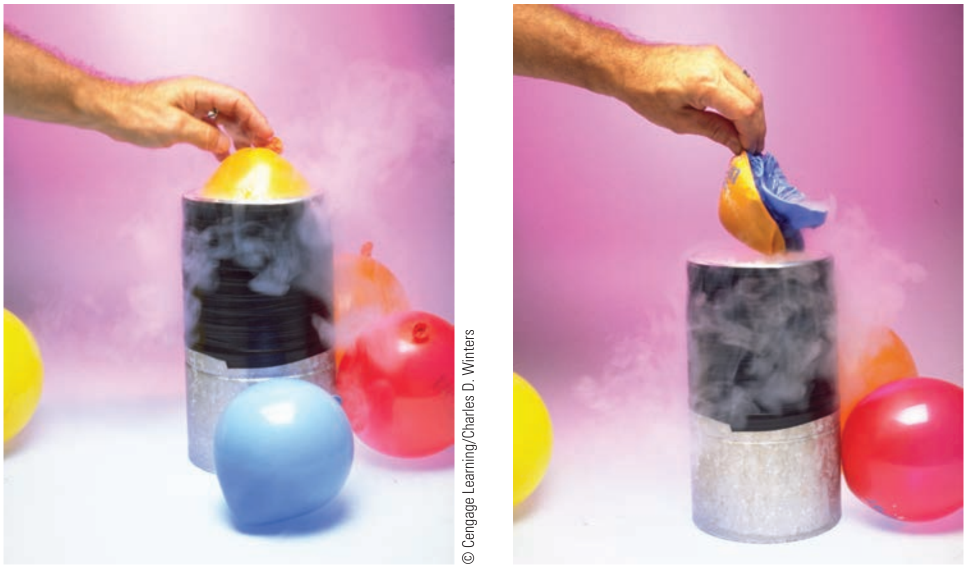
where k is an experimentally determined constant, and (remember) the measurements are made without changing the temperature of the gas. Mathematically, the pressure and volume are said to be related by an inverse relationship because the change in one is in a direction opposite (inverse) to the change in the other. That is, as the pressure on a gas sample is increased, the volume of the gas sample decreases.

Boyle's law A gas law that describes the pressure and volume behavior of a gas sample kept at constant temperature. Mathematically, it is $PV = k$.

Another gas law was discovered in 1787 by Jacques Charles, a French scientist. He studied the volume behavior of gas samples kept at constant pressure as they were heated. He found that at constant pressure, the volume of a gas sample was directly proportional to its temperature expressed in kelvins. In other words, if the temperature was doubled, the sample volume doubled as long as the pressure was kept constant (see **Figure 6.10**). This behavior, known as **Charles's law**, is represented mathematically as

$$\frac{V}{T} = k' \tag{6.5}$$

Charles's law A gas law that describes the temperature and volume behavior of a gas sample kept at constant pressure. Mathematically, it is $V/T = k'$.


© Cengage Learning/Charles D. Winters

© Cengage Learning/Charles D. Winters

FIGURE 6.10 A balloon collapses when the gas it contains is cooled in liquid nitrogen (temperature = −196°C, or 77 K). Assume the inflated yellow balloon had a volume of 4.0 L at room temperature (25°C) and the prevailing pressure. Assume the pressure remained constant and calculate the volume of the gas in the balloon at the temperature of liquid nitrogen.

or

$$V = k'T \tag{6.6}$$

where k' is another experimentally determined constant.

Boyle's law and Charles's law can be combined to give a single law called the combined gas law, which provides a relationship between the pressure, volume, and temperature of gases. The **combined gas law** is written as

$$\frac{PV}{T} = k'' \tag{6.7}$$

where k'' is another experimentally determined constant.

combined gas law A gas law that describes the pressure, volume, and temperature behavior of a gas sample. Mathematically, it is $PV/T = k''$.

Equation 6.7 can be put into a useful form by the following line of reasoning. Suppose a gas sample is initially at a pressure and temperature of P_i and T_i and has a volume of V_i. Now suppose that the pressure and temperature are changed to some new (final) values represented by P_f and T_f and that the volume changes to a new value of V_f. According to Equation 6.7,

$$\frac{P_iV_i}{T_i} = k''$$

and

$$\frac{P_fV_f}{T_f} = k''$$

Since both quotients on the left side are equal to the same constant, they can be set equal to each other, and we get

$$\frac{P_iV_i}{T_i} = \frac{P_fV_f}{T_f} \tag{6.8}$$

Example 6.6 Gas Law Calculations

Laparoscopic surgery is now widely performed to treat various abdominal diseases. Carbon dioxide (CO_2) gas is used to fill the abdominal cavity to create enough space to see and operate.

A sample of carbon dioxide gas has a volume of 5.00 L at 25°C and a pressure of 0.951 atm. What volume will the sample have if the temperature and pressure are changed to 50.°C and 1.41 atm?

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: initial $V = 5.00$ L
Unknown: final $V = ?$
initial $T = 25°C$
initial $P = 0.951$ atm
final $T = 50°C$
final $P = 1.41$ atm

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{Eq 6.8: } = \frac{P_iV_i}{T_i} = \frac{P_fV_f}{T_f}$$

Note that T in the equation is expressed in kelvins and that the Celsius temperatures need to be changed to kelvins.

$$25°\text{C} + 273 = 298 \text{ K}$$
$$50°\text{C} + 273 = 323 \text{ K}$$

STEP 3 Enter the data into the formula

$$\frac{(0.951 \text{ atm})(5.00 \text{ L})}{(298 \text{ K})} = \frac{(1.41 \text{ atm})V_f}{(323 \text{ K})}$$

The desired quantity, V_f, can be isolated by multiplying both sides of the equation by 323 K and dividing both sides by 1.41 atm:

$$\frac{(323 \cancel{\text{K}})(0.951 \cancel{\text{atm}})(5.00 \text{ L})}{(298 \cancel{\text{K}})(1.41 \cancel{\text{atm}})} = \frac{(323 \cancel{\text{K}})(\cancel{1.41 \text{ atm}})V_f}{(323 \cancel{\text{K}})(\cancel{1.41 \text{ atm}})}$$

or

$$V_f = \frac{(323\ \cancel{\text{K}})(0.951\ \cancel{\text{atm}})(5.00\ \text{L})}{(298\ \cancel{\text{K}})(1.41\ \cancel{\text{atm}})} = 3.66\ \text{L}$$

STEP 4 Check to see whether the answer makes sense.

Yes, the answer has the correct units, the correct number of significant figures and seems reasonable.

Example 6.7 More Gas Law Calculations

A patient is receiving hyperbaric therapy using oxygen gas to heal an infection. The hyperbaric chamber has a capacity of 650 L of gas. If the pressure inside the chamber is 3.00 atm at 28°C, what is the pressure value at 20°C?

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: initial $V = 650$ L
Unknown: final $P = ?$
initial $P = 3.00$ atm
initial $T = 28°\text{C}$
final $V = 650$ L
final $T = 20°\text{C}$

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{Eq. 6.8:} \ = \frac{P_iV_i}{T_i} = \frac{P_fV_f}{T_f}$$

Because the chamber is rigid, note that the volume does not change, so $V_i = V_f$

$$\text{Eq. 6.8 is reduced to } \frac{P_i}{T_i} = \frac{P_f}{T_f}$$

Note also that T in gas law equations is expressed in kelvins and that the Celsius temperatures need to be changed to kelvins.

$$28°\text{C} + 273 = 301\ \text{K}$$
$$20°\text{C} + 273 = 293\ \text{K}$$

STEP 3 Enter the data into the formula.

$$\frac{3.00\ \text{atm}}{301\ \text{K}} = \frac{P_f}{293\ \text{K}}$$

The desired quantity, P_f, can be isolated by multiplying both sides of the equation by 298 K.

$$\frac{(3.00\ \text{atm})(295\ \cancel{\text{K}})}{301\ \cancel{\text{K}}} = \frac{(P_f)(\cancel{298\ \text{K}})}{\cancel{298\ \text{K}}}$$

or

$$P_f = \frac{(3.00\ \text{atm})(298)}{301} = 2.97\ \text{atm}$$

STEP 4 Check to see whether the answer makes sense.

Yes, the answer has the correct units and seems reasonable.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

✔ LEARNING CHECK 6.6

a. A sample of argon gas is confined in a 10.0 L container at a pressure of 1.90 atm and a temperature of 30.°C. What volume would the sample have at 1.00 atm and −10.2°C?

b. A sample of gas has a volume of 5.00×10^2 mL at a temperature and pressure of 300. K and 800. torr. It is desired to compress the sample to a volume of 250. mL at a pressure of 900. torr. What temperature in both kelvins and Celsius degrees will be required?

6.8 The Ideal Gas Law

Learning Objective 6 Do calculations based on the ideal gas law.

The combined gas law (Equation 6.8) works only for samples in which the mass of gas remains constant during changes in temperature, pressure, and volume. However, it is often useful to work with situations in which the amount of gas varies. The foundation for this kind of work was proposed in 1811 by Amadeo Avogadro, an Italian scientist. According to his proposal, which is now known as **Avogadro's law**, equal volumes of different gases measured at the same temperature and pressure contain equal numbers of gas molecules. According to this idea, two identical compressed gas cylinders of helium and oxygen at the same pressure and temperature would contain identical numbers of molecules of the respective gases. However, the mass of gas in the cylinders would *not* be the same because the molecules of the two gases have different molecular weights.

Avogadro's law Equal volumes of gases measured at the same temperature and pressure contain equal numbers of molecules.

The actual temperature and pressure used do not influence the validity of Avogadro's law, but it is convenient to specify a standard set of values. Chemists have chosen 0°C (273 K) and 1.00 atm to represent what are called **standard conditions** for gas measurements. These conditions are often abbreviated as STP (standard temperature and pressure).

standard conditions (STP) A set of specific temperature and pressure values used for gas measurements.

As we have seen, the mole (defined in **Section 2.6**) is a convenient quantity of matter to work with. What volume does 1.00 mol of a gas occupy according to Avogadro's law? Experiments show that 1.00 mol of any gas molecules has a volume of 22.4 L at STP (see **Figure 6.11**).

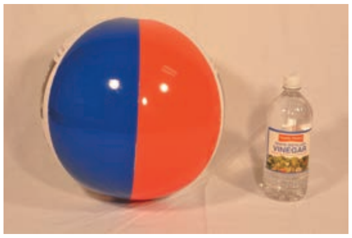

© Spencer L. Seager

FIGURE 6.11 The ball has a volume of 22.4 L, the volume of 1 mol of any gas at STP. The bottle has a volume of 1.00 quart (0.946 L). How many moles of gas would the bottle contain at STP?

A combination of Boyle's, Charles's, and Avogadro's laws leads to another gas law that includes the quantity of gas in a sample as well as the temperature, pressure, and volume of the sample. This law, known as the **ideal gas law**, is written as

$$PV = nRT \tag{6.9}$$

In this equation, P, V, and T are defined as they were in the gas laws given earlier. The symbol n stands for the number of moles of gas in the sample being used, and R is a constant known as the **universal gas constant**. The measured value for the volume of 1.00 mol of gas at STP allows R to be evaluated by substituting the values into Equation 6.9 after rearrangement to isolate R:

$$R = \frac{PV}{nT} = \frac{(1.00\text{ atm})(22.4\text{ L})}{(1.00\text{ mol})(273\text{ K})} = 0.0821\frac{\text{L atm}}{\text{mol K}}$$

This value of R is the same for all gases under any conditions of temperature, pressure, and volume.

ideal gas law A gas law that relates the pressure, volume, temperature, and number of moles in a gas sample. Mathematically, it is $PV = nRT$.

universal gas constant The constant that relates pressure, volume, temperature, and number of moles of gas in the ideal gas law.

Example 6.8 Ideal Gas Law Calculations

Nitrous oxide (N_2O), is an inhaled gas used as a pain medication during childbirth, following trauma, and as a part of end-of-life care.

Use the ideal gas law to calculate the volume of 0.413 mol of nitrous oxide gas at a temperature of 20.°C and a pressure of 1.20×10^3 torr.

Solution

STEP 1 Examine the question for what is given and what is unknown.

$$\text{Given: } n = 0.413 \text{ mol}$$
$$\text{Unknown: } V = ?$$
$$T = 20°\text{C}$$
$$P = 1.20 \times 10^3 \text{ torr}$$

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{Eq. 6.9: } PV = nRT \text{ (the ideal gas law)}$$

Because volume is the desired quantity, we isolate it by dividing both sides of the ideal gas law by P:

$$\frac{PV}{P} = \frac{nRT}{P} \quad \text{or} \quad V = \frac{nRT}{P}$$

To use the ideal gas law (Equation 6.9), it is necessary that all units match those of R. Thus, the temperature will have to be expressed in kelvins and the pressure in atmospheres:

$$\text{K} = °\text{C} + 273 = 20°\text{C} + 273 = 293 \text{ K}$$

$$P = (1.20 \times 10^3 \cancel{\text{torr}})\left(\frac{1 \text{ atm}}{760 \cancel{\text{torr}}}\right) = 1.58 \text{ atm}$$

STEP 3 Enter the data into the formula:

$$V = \frac{(0.413 \cancel{\text{mol}})\left(0.0821 \frac{L \cancel{\text{atm}}}{\cancel{\text{mol}} \cancel{\text{K}}}\right)(293 \cancel{\text{K}})}{(1.58 \cancel{\text{atm}})} = 6.29 \text{ L}$$

STEP 4 Check to see whether the answer makes sense.

Yes, the answer has the correct units. The correct number of significant figures seems reasonable.

> ✔ **LEARNING CHECK 6.7** A 2.15 mol sample of sulfur dioxide gas (SO_2) occupies a volume of 12.6 L at 30.°C. What is the pressure of the gas in atm?

Because R is a constant for all gases, it follows that if any three of the quantities P, V, T, or n are known for a gas sample, the fourth quantity can be calculated by using Equation 6.9. An interesting application of this concept makes it possible to determine the molecular weights of gaseous substances. If the mass of a sample is known, the number of moles in the sample is the mass in grams divided by the molecular weight. This fact is represented by Equation 6.10, where n is the number of moles in a sample that has a mass in grams of m and a molecular weight of MW:

$$n = \frac{m}{\text{MW}} \tag{6.10}$$

When $\frac{m}{\text{MW}}$ is substituted for n in Equation 6.9, the result is

$$PV = \frac{mRT}{\text{MW}} \tag{6.11}$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 6.9 More Ideal Gas Law Calculations

A gas sample has a volume of 2.74 L and a mass of 16.12 g and is stored at a pressure of 4.80 atm at a temperature of 25°C. The gas might be CH_4, C_2H_6, or C_3H_{10}. Which gas is it?

Solution

The molecular weight of the gas is determined using Equation 6.11 and compared with the molecular weights of the three possibilities calculated from their formulas. Rearrangement of Equation 6.11 to isolate molecular weight gives

$$\text{MW} = \frac{mRT}{PV}$$

Substitution of the known quantities after conversion to proper units gives

$$\text{MW} = \frac{mRT}{PV} = \frac{(16.12\ \text{g})\left(0.0821\frac{\cancel{\text{L}}\ \cancel{\text{atm}}}{\text{mol}\ \cancel{\text{K}}}\right)(298\ \cancel{\text{K}})}{(4.80\ \cancel{\text{atm}})(2.74\ \cancel{\text{L}})} = 30.0\ \text{g/mol}$$

Thus, the molecular weight is 30.0 u. This matches the molecular weight of C_2H_6 calculated from atomic weights and the molecular formula.

✓ **LEARNING CHECK 6.8** A sample of unknown gas has a mass of 3.35 g and occupies 2.00 L at 1.21 atm and 27°C. What is the molecular weight of the gas? Is the gas H_2S, HBr, or NH_3?

The gas laws discussed in this chapter apply only to gases that are ideal, but interestingly, no ideal gases actually exist. If they did exist, ideal gases would behave exactly as predicted by the gas laws at all temperatures and pressures. Real gases deviate from the behavior predicted by the gas laws, but under normally encountered temperatures and pressures, the deviations are small for many real gases. This fact allows the gas laws to be used for real gases. Interparticle attractions tend to make gases behave less ideally. Thus, the gas laws work best for gases in which such forces are weak, that is, those made up of single atoms (the noble gases) or nonpolar molecules (O_2, N_2, etc.). Highly polar molecules such as water vapor, hydrogen chloride, and ammonia deviate significantly from ideal behavior.

6.9 Dalton's Law

Learning Objective 7 Do calculations based on Dalton's law.

John Dalton (1766–1844), an English schoolteacher, made a number of important contributions to chemistry. Some of his experiments led to the law of partial pressures, also called **Dalton's law**. According to this law, the total pressure exerted by a mixture of different gases kept at a constant volume and temperature is equal to the sum of the partial pressures of the gases in the mixture. The **partial pressure** of each gas in such mixtures is the pressure each gas would exert if it were confined alone under the same temperature and volume conditions as the mixture.

Dalton's law of partial pressures The total pressure exerted by a mixture of gases is equal to the sum of the partial pressures of the gases in the mixture.

partial pressure The pressure an individual gas of a mixture would exert if it were in the container alone at the same temperature as the mixture.

Imagine you have four identical gas containers, as shown in **Figure 6.12**. Place samples of three different gases (represented by △, ○, and □) into three of the containers, one to a container, and measure the pressure exerted by each sample. Then place all three samples into the fourth container and measure the total pressure (P_t) exerted. The result is a statement of Dalton's law:

$$P_t = P_{\triangle} + P_{\bigcirc} + P_{\square} \qquad (6.12)$$

where $P_{\triangle}$, $P_{\bigcirc}$, and $P_{\square}$ are the partial pressures of gases △, ○, and □, respectively.

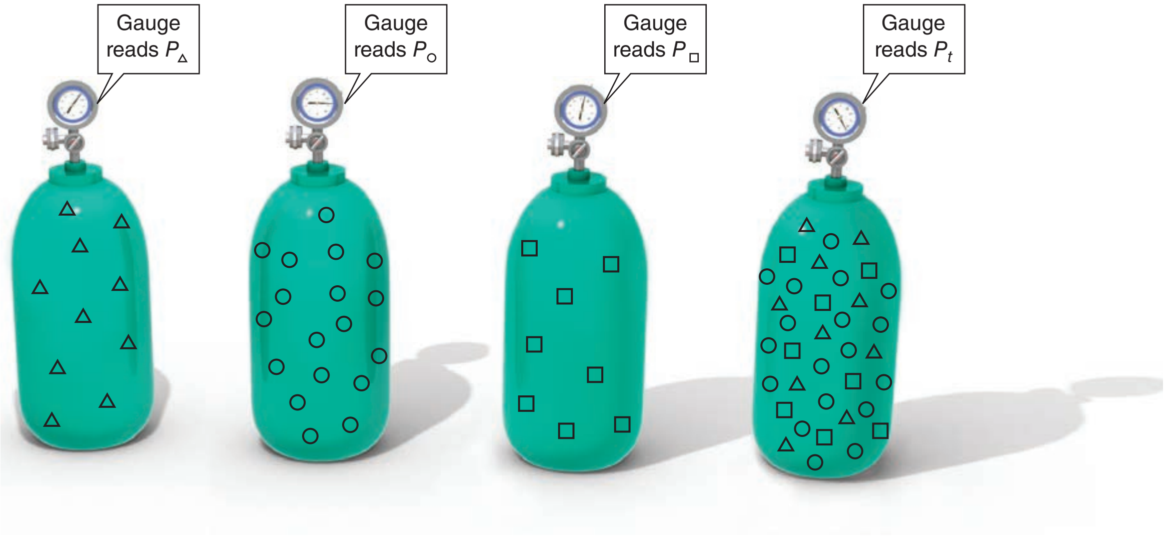


FIGURE 6.12 Dalton's law of partial pressures.

Example 6.10 Partial Pressure Calculations

Medical grade compressed air is used in just about every area of a hospital and is administered to patients who need inhaled medications, for treatment of respiratory conditions, and to power ventilators.

A sample of compressed air is collected when the atmospheric pressure is 742 torr. The partial pressures of nitrogen and oxygen in the sample are found to be 581 torr and 141 torr, respectively. Assume water vapor to be the only other gas present in the air sample, and calculate its partial pressure.

Solution

Dalton's law says $P_t = P_{O_2} + P_{N_2} + P_{H_2O}$. The total pressure of the sample is the atmospheric pressure of 742 torr. Therefore,

$$742 \text{ torr} = 141 \text{ torr} + 581 \text{ torr} + P_{H_2O}$$

and

$$P_{H_2O} = 742 - 141 - 581 = 20. \text{ torr}$$

✔ **LEARNING CHECK 6.9** A mixture is made of helium, nitrogen, and oxygen. Their partial pressures are, respectively, 310 torr, 0.200 atm, and 7.35 psi. What is the total pressure of the mixture in torr?

6.10 Graham's Law

Learning Objective 8 Do calculations based on Graham's law.

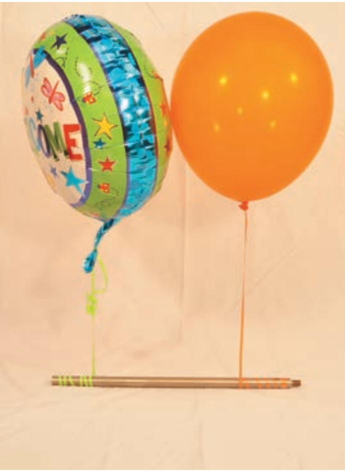
Effusion and diffusion are processes by which gases move and mix. **Effusion** is the escape of a gas through a small hole in its container. **Diffusion** is the process in which two or more gases spontaneously intermingle when brought together. Even though the processes appear to be different, they are related, and both follow a law proposed in 1828 by Thomas Graham to describe effusion (see **Figure 6.13**). For two gases, represented by A and B, **Graham's law** is

$$\frac{\text{effusion rate } A}{\text{effusion rate } B} = \sqrt{\frac{\text{molecular mass of } B}{\text{molecular mass of } A}} \qquad (6.13)$$

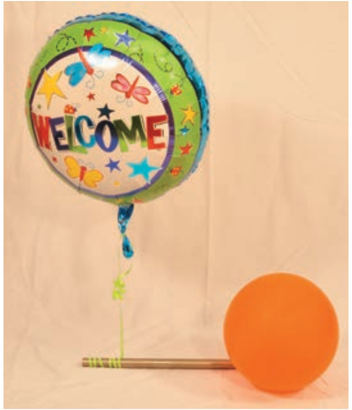
effusion A process in which a gas escapes from a container through a small hole.

diffusion A process that causes gases to spontaneously intermingle when they are brought together.

Graham's law A mathematical expression that relates rates of effusion or diffusion of two gases to the masses of the molecules of the two gases.


© Jeffrey M. Seager

1. A mylar balloon (left) and rubber balloon freshly filled with helium.


© Jeffrey M. Seager

2. The same balloons the next day.

FIGURE 6.13 Graham's law in action. Does helium diffuse more rapidly through rubber or plastic?

Example 6.11 Graham's Law Calculations

Oxygen molecules weigh 16 times as much as hydrogen molecules. Which molecule will diffuse faster and how much faster?

Solution

Applying Equation 6.13 but recognizing that diffusion follows the equation as well as effusion, we get

$$\frac{\text{rate } H_2}{\text{rate } O_2} = \sqrt{\frac{\text{mass } O_2}{\text{mass } H_2}} = \sqrt{\frac{32}{2.0}} = \sqrt{16} = 4.0$$

Therefore, we conclude that hydrogen will diffuse four times faster than oxygen.

✔ **LEARNING CHECK 6.10** Which will diffuse faster, He molecules or Ne molecules? How much faster?

6.11 Changes in State

Learning Objective 9 Classify changes in state as exothermic or endothermic.

Matter can be changed from one state into another by processes such as heating, cooling, or changing the pressure. Heating and cooling are the processes most often used. A change in state that requires an input of heat is called endothermic, whereas one in which heat is given up (or removed) is called exothermic (see **Section 5.8**). (These terms come from the Greek *endo* = in and *exo* = out). Endothermic changes are those in which particles are moved farther apart as cohesive forces are being overcome, such as the change of a solid to a liquid or gas. Exothermic changes are those in the opposite direction. See **Figure 6.14**.

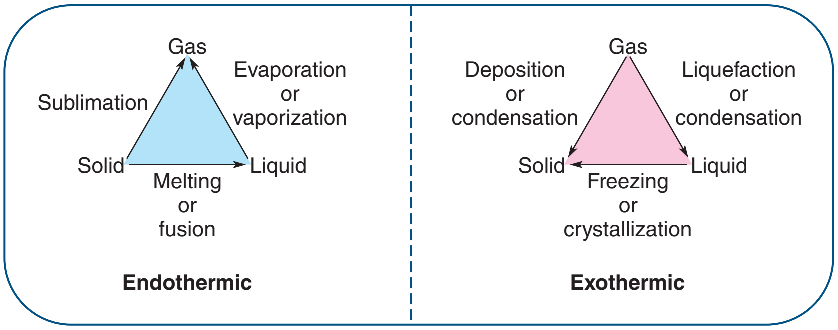

Gas
Sublimation
Evaporation or vaporization
Solid
Liquid
Melting or fusion
Endothermic
Gas
Deposition or condensation
Liquefaction or condensation
Solid
Liquid
Freezing or crystallization
Exothermic

FIGURE 6.14 Endothermic and exothermic changes of state.

✔ **LEARNING CHECK 6.11** Classify the following processes as endothermic or exothermic:

a. Alcohol evaporates.
b. Water freezes.
c. Iron melts in a furnace.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

6.12 Evaporation and Vapor Pressure

Learning Objective 10 Demonstrate an understanding of the concepts of vapor pressure and evaporation.

The evaporation of liquids is a familiar process. Water in a container will soon disappear (evaporate) if the container is left uncovered. **Evaporation**, or **vaporization**, is an endothermic process that takes place as a result of molecules leaving the surface of a liquid. The rate of evaporation depends on the temperature of the liquid and the surface area from which the molecules can escape. Temperature is an important factor because it is related directly to the speed and kinetic energy of the molecules and hence their ability to break away from the attractive forces present at the liquid's surface.

evaporation or **vaporization** An endothermic process in which a liquid is changed to a gas.

Evaporating molecules carry significant amounts of kinetic energy away from the liquid, and as a result, the temperature of the remaining liquid will drop unless heat flows in from the surroundings. This principle is involved in all evaporative cooling processes, including evaporative coolers for homes, the cooling of the human body by perspiration, and the cooling of a panting dog by the evaporation of saliva from the mucous membranes of its mouth.

Compare evaporation in a closed container (see **Figure 6.15**) with that in an open container. Evaporation occurs in both containers, as indicated by a drop in liquid level. But, unlike that in an open container, the liquid level in the closed container eventually stops dropping and becomes constant.

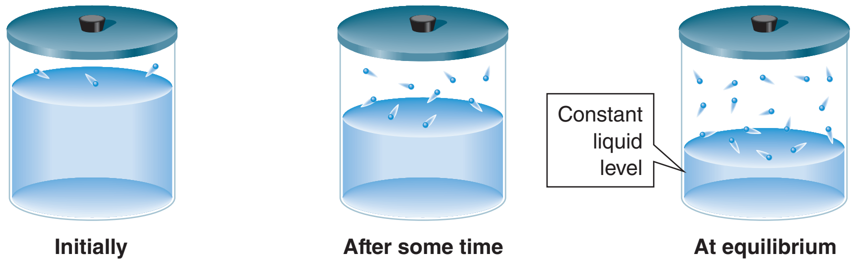


FIGURE 6.15 Liquid evaporation in a closed container. The drop in liquid level is greatly exaggerated for emphasis.

What would explain this behavior? In a closed container the molecules of liquid that go into the vapor (gaseous) state are unable to move completely away from the liquid surface as they do in an open container. Instead, the vapor molecules are confined to a space immediately above the liquid, where they have many random collisions with the container walls, other vapor molecules, and the liquid surface. Occasionally, their collisions with the liquid result in condensation, and they are recaptured by the liquid. **Condensation** is an exothermic process in which a gas or vapor is converted to either a liquid or a solid (see **Figure 6.16**). Thus, two processes—evaporation (escape) and condensation (recapture)—actually take place in the closed container. Initially, the rate of evaporation exceeds that of condensation, and the liquid level drops. However, the rates of the two processes eventually become equal, and the liquid level stops dropping because the number of molecules that escape in a given time is the same as the number recaptured.

condensation An exothermic process in which a gas or vapor is changed to a liquid or solid.

sethink/10 images/Pixabay

FIGURE 6.16 The formation of dew is a common example of condensation.

A system in which two opposite processes take place at equal rates is said to be in equilibrium (see **Chapter 8**). Under the equilibrium conditions just described, the number of molecules in the vapor state remains constant. This constant number of molecules will exert a constant pressure on the liquid surface and the container walls. This pressure exerted by a vapor in equilibrium with a liquid is called the **vapor pressure** of the liquid. The magnitude of a vapor pressure depends on the nature of the liquid (molecular polarity, mass, etc.) and the temperature of the liquid. These dependencies are illustrated in **Tables 6.4** and **6.5**.

vapor pressure The pressure exerted by vapor that is in equilibrium with its liquid.

TABLE 6.4 The Vapor Pressure of Various Liquids at 20°C

Liquid	Molecular Weight (u)	Polarity	Vapor Pressure (torr)
pentane (C_5H_{12})	72	Nonpolar	414.5
hexane (C_6H_{14})	86	Nonpolar	113.9
heptane (C_7H_{16})	100	Nonpolar	37.2
ethanol (C_2H_5—OH)	46	Polar (hydrogen bonds)	43.9
1-propanol (C_3H_7—OH)	60	Polar (hydrogen bonds)	17.3
1-butanol (C_4H_9—OH)	74	Polar (hydrogen bonds)	7.1

The effect of molecular mass on vapor pressure is seen in both the pentane–heptane and ethanol–1-butanol series of compounds in **Table 6.4**. Within each series, the molecular polarities are the same for each member, but vapor pressure decreases as molecular weight increases. This shows the effect of stronger dispersion forces between heavier molecules. A comparison of pentane and 1-butanol shows the effects of polar attractions between molecules. Molecules of these liquids have similar molecular weights, but the hydrogen-bonded 1-butanol has a much lower vapor pressure.

The effect of increasing the kinetic energy of molecules by heating is clearly evident by the vapor pressure behavior of water shown in **Table 6.5**.

TABLE 6.5 Vapor Pressure of Water at Various Temperatures

Temperature (°C)	Vapor Pressure (torr)
0	4.6
20	17.5
40	55.3
60	149.2
80	355.5
100	760.0

✔ **LEARNING CHECK 6.12** Decide which member of each of the following pairs of compounds would have the higher vapor pressure. Explain your choice in each case.

a. Methyl alcohol (CH_3OH) and propyl alcohol (C_3H_7OH)
b. Liquid helium (He) and liquid nitrogen (N_2)
c. Liquid hydrogen fluoride (HF) and liquid neon (Ne)

6.13 Boiling and the Boiling Point

Learning Objective 11 Demonstrate an understanding of the process of boiling and the concept of boiling point.

boiling point The temperature at which the vapor pressure of a liquid is equal to the prevailing atmospheric pressure.

normal or **standard boiling point** The temperature at which the vapor pressure of a liquid is equal to 1 standard atmosphere (760 torr).

As a liquid is heated, its vapor pressure increases, as shown for water in **Table 6.5**. If the liquid's temperature is increased enough, its vapor pressure will reach a value equal to that of the prevailing atmospheric pressure. Up to that temperature, all vaporization appears to take place at the liquid surface. However, when the vapor pressure becomes equal to atmospheric pressure, vaporization begins to occur beneath the surface as well. When bubbles of vapor form and rise rapidly to the surface, where the vapor escapes, the liquid is boiling (see **Figure 6.17**). The **boiling point** of a liquid is the temperature at which the vapor pressure of a liquid is equal to the atmospheric pressure above the liquid. The **normal** or **standard boiling point** of a liquid is the temperature at which the vapor pressure is equal to 1 standard atmosphere (760 torr). Normal values were used in all examples of boiling points given earlier in this book.

Liquids boil at temperatures higher than their normal boiling points when external pressures are greater than 760 torr. When external pressures are less than 760 torr, liquids boil at temperatures below their normal boiling points. Thus, the boiling point of water fluctuates with changes in atmospheric pressure. Such fluctuations seldom exceed 2°C at a specific location, but there can be striking variations at different elevations, as shown by **Figure 6.18**. (This is why cooking directions are sometimes different for different altitudes.)

rommex/iStock/Getty Images

FIGURE 6.17 As the temperature of a liquid reaches the boiling point, bubbles of vapor form within the liquid and rise to the surface.

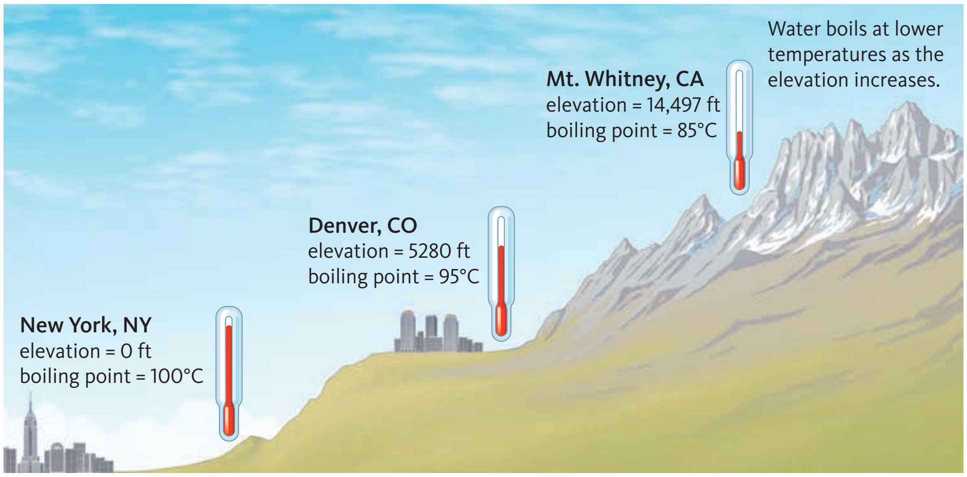


FIGURE 6.18 Variations in the boiling point of water with elevation.

The increase in boiling point caused by an increase in pressure is the principle used in the ordinary pressure cooker. Increasing the pressure inside the cooker causes the boiling point of the water in it to rise, as shown in **Table 6.6**. It then becomes possible to increase the temperature of the food-plus-water in the cooker above 100°C. Such an increase of just 10°C will make the food cook approximately twice as fast (see **Figure 6.19**).

TABLE 6.6 The Boiling Point of Water in a Pressure Cooker

Pressure above Atmospheric psi	Pressure above Atmospheric torr	Boiling Point of Water (°C)
5	259	108
10	517	116
15	776	121

DenGuy/E+/Getty Images

FIGURE 6.19 An autoclave, used to sterilize medical instruments, functions like a pressure cooker, with higher temperatures and shorter required times to accomplish its task.

6.14 Sublimation and Melting

Learning Objective 12 Demonstrate an understanding of the processes of sublimation and melting.

sublimation The endothermic process in which a solid is changed directly to a gas without first becoming a liquid.

Solids, like liquids, have vapor pressures. Although the motion of particles is much more restricted in solids, particles at the surface can escape into the vapor state if they acquire sufficient energy. However, the strong cohesive forces characteristic of the solid state usually cause the vapor pressures of solids to be quite low.

As expected, vapor pressures of solids increase with temperature. When the vapor pressure of a solid is high enough to allow escaping molecules to go directly into the vapor state without passing through the liquid state, the process is called **sublimation** (see **Figure 6.20**). Sublimation is characteristic of materials such as solid carbon dioxide (dry ice) and naphthalene (moth crystals). Frozen water also sublimes under appropriate conditions. Wet laundry hung out in freezing weather eventually dries as the frozen water sublimes. Freeze drying, a technique based on this process, is used to remove water from materials that would be damaged by heating (e.g., freeze-dried foods).

Even though solids have vapor pressures, most pure substances in the solid state melt before appreciable sublimation takes place. Melting involves the breakdown of a rigid, orderly, solid structure into a mobile, disorderly liquid state. This collapse of the solid structure occurs at a characteristic temperature called the **melting point**. At the melting point, the kinetic energy of solid particles is large enough to partially overcome the strong cohesive forces holding the particles together, and the solid and liquid states have the same vapor pressure.

© Jeffrey M. Seager

FIGURE 6.20 Solid CO_2 (left) and solid H_2O (right) both sublime. Contrast the endothermic processes involved when each is used in the most common way to keep things cold. Are the same processes involved?

melting point The temperature at which a solid changes to a liquid; the solid and liquid have the same vapor pressure.

decomposition A change in chemical composition that can result from heating.

In some instances, solids cannot be changed into liquids, or liquids into gases, by heating. The atoms making up the molecules of some solids acquire enough kinetic energy on heating to cause bonds within the molecules to break before the solid (or liquid) can change into another state. This breaking of bonds within molecules changes the composition of the original substance. When this **decomposition** occurs, the original substance is said to have decomposed. This is why cotton and paper, when heated, char rather than melt.

6.15 Energy and the States of Matter

Learning Objective 13 Do calculations based on energy changes that accompany heating, cooling, or changing the state of a substance.

A pure substance in the gaseous state contains more energy than in the liquid state, which in turn contains more energy than in the solid state. Before we look at this, note the following relationships. Kinetic energy, the energy of particle motion, is related to heat. In fact, temperature is a measurement of the average kinetic energy of the particles in a system. Potential energy, in contrast, is related to particle separation distances rather than motion. Thus, we conclude that an increase in temperature on adding heat corresponds to an increase in kinetic energy of the particles, whereas no increase in temperature on adding heat corresponds to an increase in the potential energy of the particles.

Now let's look at a system composed of 1 g of ice at an initial temperature of −20°C. Heat is added at a constant rate until the ice is converted into 1 g of steam at 120°C. The atmospheric pressure is assumed to be 760 torr throughout the experiment. The changes in the system take place in several steps, as shown in **Figure 6.21**.

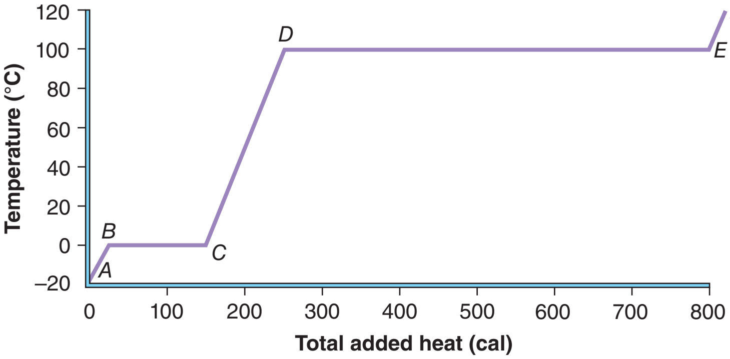


FIGURE 6.21 The temperature behavior of a system during changes in state.

The solid is first heated from −20°C to the melting point of 0°C (line *AB*). The temperature increase indicates that most of the added heat causes an increase in the kinetic energy of the molecules. Along line *BC,* the temperature remains constant at 0°C while the solid melts. The constant temperature during melting reveals that the added heat has increased the potential energy of the molecules without increasing their kinetic energy; the molecules are moved farther apart, but their motion is not increased. The addition of more heat warms the liquid water from 0°C to the normal boiling point (see **Figure 6.22**) of 100°C (line *CD*). At 100°C, another change of state occurs as heat is added, and the liquid is converted into vapor (steam) at 100°C (line *DE*). The constant temperature of this process again indicates an increase in potential energy. Line *EF* represents heating the steam from 100°C to 120°C by adding more heat.

Rickett
BOIL
WATER
NOTICE

© Gillis Benedict/Livingston Daily via Imagn Content Services, LLC

FIGURE 6.22 Boiling water kills or inactivates bacteria and other pathogens. Boil water notices are used by health agencies in response to biological contamination of drinking water.

The addition of heat to this system resulted in two obviously different results: The temperature of water in a specific state was increased, or the water was changed from one state to another at constant temperature. The amount of heat energy required to change the temperature of a specified amount of a substance by 1°C is called the **specific heat** of the substance. In scientific work, this is often given in units of calories or joules (J) per gram degree. Thus, the specific heat of a substance is the number of calories or joules required

specific heat The amount of heat energy required to raise the temperature of exactly 1 g of a substance by exactly 1°C.

HEALTH CONNECTIONS 6.2

Therapeutic Uses of Oxygen Gas

A steady supply of oxygen is essential for the human body to function properly. The most common source of this gas is inhaled air, in which the partial pressure of oxygen is about 160 torr. In a healthy individual, this partial pressure is high enough to allow sufficient oxygen for body processes to be transported into the blood and distributed throughout the body. Patients suffering from a lung disease, such as pneumonia or emphysema, often cannot transport sufficient oxygen to the blood from the air they breathe unless the partial pressure of oxygen in the air is increased. This is done by mixing an appropriate amount of oxygen with the air by using an oxygen mask or nasal cannula.

Oxygen at very high partial pressures is used in other clinical applications based on a technique called *hyperbaric oxygenation.* In one application, patients infected by anaerobic bacteria, such as those that cause tetanus and gangrene, are placed in a hyperbaric chamber in which the partial pressure of oxygen is 3 to 4 standard atmospheres (2.2×10^3 to 3.0×10^3 torr). Because of the high partial pressure, body tissues pick up large amounts of oxygen, and the bacteria are killed.

Hyperbaric oxygenation may also be used to treat other abnormal conditions or injuries, such as certain heart disorders, carbon monoxide poisoning, crush injuries, certain hard-to-treat bone infections, smoke inhalation, near-drowning, asphyxia, and burns.

Universal Images Group/Getty Images

Hyperbaric chambers must be strongly built to resist significant internal gas pressure.

to raise the temperature of 1 g of the substance by 1°C. (*Note:* 1 cal = 4.184 J.) The specific heat is related to the amount of heat required to increase the temperature of a sample of substance, as shown in Equation 6.14.

$$\text{Heat} = (\text{sample mass})\,(\text{specific heat})\,(\text{temp. change}) \tag{6.14}$$

Specific heats for a number of substances in various states are listed in **Table 6.7**. A substance with a high specific heat is capable of absorbing more heat with a small temperature change than substances with lower specific heats. Thus, substances to be used as heat transporters (e.g., in cooling and heating systems) should have high specific heats—note the value for liquid water.

Example 6.12 Specific Heat Calculations

You notice that your car is running hot on a summer day. Someone tells you to drain out the ethylene glycol antifreeze and replace it with water. Will this allow the engine to run cooler?

Solution

The engine will run cooler because a given mass of water has a greater ability to carry heat from the engine to the radiator than does an equal mass of ethylene glycol. The coolant in your car is a mixture of ethylene glycol and water, but to simplify the following comparison, let us imagine it is pure ethylene glycol. We calculate the amount of heat absorbed by 1000. g each of pure ethylene glycol and pure water as the temperature changes from 20°C to 80°C.

$$\text{Heat absorbed} = (\text{mass})(\text{specific heat})(\text{temp. change})$$

$$\text{ethylene glycol:}\qquad \text{Heat absorbed} = (1000.\ \cancel{g})\left(\frac{0.57\ \text{cal}}{\cancel{g}\ {}^\circ\cancel{C}}\right)(60^\circ\ \cancel{C})$$

$$= 34{,}200\ \text{cal} = 34.2\ \text{kcal}$$

$$\text{water:}\qquad \text{Heat absorbed} = (1000.\ \cancel{g})\left(\frac{1.00\ \text{cal}}{\cancel{g}\ {}^\circ\cancel{C}}\right)(60^\circ\ \cancel{C})$$

$$= 60{,}000\ \text{cal} = 60.0\ \text{kcal}$$

Thus, the same amount of water will absorb (and transport) nearly twice as much heat for the same temperature increase.

✔ **LEARNING CHECK 6.13** Some nuclear reactors are cooled by gases. Calculate the number of calories that 1.00 kg of helium gas will absorb when it is heated from 25°C to 700°C. See **Table 6.7** for the specific heat of He.

TABLE 6.7 Specific Heats for Selected Substances

Substance and State	Specific Heat cal/g Degree	 J/g Degree
Aluminum (solid)	0.24	1.0
Copper (solid)	0.093	0.39
Ethylene glycol (liquid)	0.57	2.4
Helium (gas)	1.25	5.23
Hydrogen (gas)	3.39	14.2
Lead (solid)	0.031	0.13
Mercury (liquid)	0.033	0.14
Nitrogen (gas)	0.25	1.1
Oxygen (gas)	0.22	0.92
Sodium (solid)	0.29	1.2
Sodium (liquid)	0.32	1.3
Water (solid)	0.51	2.1
Water (liquid)	1.00	4.18
Water (gas)	0.48	2.0

heat of fusion The amount of heat energy required to melt exactly 1 g of a solid substance at constant temperature.

heat of vaporization The amount of heat energy required to vaporize exactly 1 g of a liquid substance at constant temperature.

Image Source/Photodisc/Getty Images

FIGURE 6.23 Whether you are working with steam pipes or in the kitchen, steam can cause severe burns.

The amount of heat required to change the state of 1 g of a substance at constant temperature is called the **heat of fusion** (for melting a solid) and the **heat of vaporization** (for boiling a liquid). The units used for these quantities are just calories, or joules, per gram because no temperature changes are involved. These heats represent the amount of energy required to change 1 g of a substance to the liquid or vapor state at the characteristic melting or boiling point. The heats of fusion and vaporization for water are 80 and 540 cal/g, respectively. This explains why a burn caused by steam at 100°C is more severe than one caused by water at 100°C. Vaporization has added 540 cal to each gram of steam, and each gram will release these 540 cal when it condenses on the skin. Liquid water at 100°C would not have this extra heat with which to burn the skin (see **Figure 6.23**).

STUDY TOOLS 6.1

Which Gas Law to Use

For many students, the biggest challenge of this chapter is solving problems using the gas laws. Once you recognize that you are faced with a gas law problem, you must decide which of the six gas laws will work to solve the problem. One aid to selecting the appropriate law is to look for key words, phrases, or ideas that are often associated with specific laws. Some of these are given here:

Gas Law	Equation	Key
Boyle's law	$PV = k$	T is constant
Charles's law	$\frac{V}{T} = k'$	P is constant
Combined gas law	$\frac{P_iV_i}{T_i} = \frac{P_fV_f}{T_f}$	P, V, and T all change
Dalton's law	$P_t = P_\triangle + P_\bigcirc + P_\square$	Two or more different gases
Graham's law	$\frac{\text{effusion rate } A}{\text{effusion rate } B} = \sqrt{\frac{\text{molecular mass of } B}{\text{molecular mass of } A}}$	Effusion and diffusion
Ideal gas law	$PV = nRT$	Moles of gas

For example, if you see the key word *diffusion*, it is likely that you are dealing with a Graham's law problem.

The first three gas laws (Boyle's, Charles's, and the combined) are very similar in that they all use the symbols P, V, and T. If you have narrowed down a gas law problem to one of these three, a simple approach is to use the combined gas law. It works in all three cases. If T is constant,

$$\frac{P_iV_i}{T_i} = \frac{P_fV_f}{T_f}$$

simplifies to $P_iV_i = P_fV_f$, a form of Boyle's law. If P is constant, it simplifies to

$$\frac{V_i}{T_i} = \frac{V_f}{T_f}$$

a form of Charles's law. If V is constant, the combined law becomes

$$\frac{P_i}{T_i} = \frac{P_f}{T_f}$$

an equation that is not named but is useful for certain problems.

A final point to remember is that temperatures must be expressed in kelvins to get correct answers using any of the gas laws that involve temperature.

Example 6.13 More Specific Heat Calculations

Steam rooms can be used to break up the congestion in the sinuses and lungs, helping to treat colds and aid breathing.

Calculate the heat released when 5.0 kg of steam at 120.°C condenses to water at 100.°C in a radiator of a steam heating system.

Solution

Consider the process as taking place in two steps. The steam must cool from 120.°C to 100.°C and then condense to liquid water at 100.°C. When the steam cools to 100.°C,

$$\begin{aligned}\text{Heat released} &= (\text{mass})(\text{specific heat})(\text{temp. change})\\ &= (5.0\times10^3\ \cancel{\text{g}})\left(\frac{0.48\ \text{cal}}{\cancel{\text{g}}\ \cancel{^\circ\text{C}}}\right)(20.^\circ\ \cancel{\text{C}})\\ &= 4.8\times10^4\ \text{cal} = 48\ \text{kcal}\end{aligned}$$

When the steam condenses to liquid water at 100.°C,

$$\begin{aligned}\text{Heat released} &= (\text{mass})(\text{heat of vaporization})\\ &= (5.0\times10^3\ \cancel{\text{g}})\left(\frac{540\ \text{cal}}{\cancel{\text{g}}}\right)\\ &= 2.7\times10^6\ \text{cal} = 2.7\times10^3\ \text{kcal}\end{aligned}$$

Note that the heat of vaporization was used even though the water was changing from the vapor to the liquid state. The only difference between vaporization and condensation is the direction of heat flow; the amount of heat involved remains the same for a specific quantity of material. (Accordingly, 1 g of liquid water will release 80 cal when it freezes.)

These results make it clear that most of the transported heat (98%) was carried in the form of potential energy, which was released when the steam condensed.

✔ **LEARNING CHECK 6.14** Suppose the radiator of your car overheats and begins to boil. Calculate the number of calories absorbed by 5.00 kg of water (about 1 gallon) as it boils and changes to steam.

Environmental Career Description:

FIELD CHEMIST

Field chemists collect samples at various sites—often at landfills, water-treatment plants, or mine-reclamation sites, including any site suspected to have, or being monitored for, pollutants. Environmental Protection Agency (EPA) standards dictate that landfills and reclamation sites meet certain parameters. Site managers must report data proving that they meet these standards. Independent laboratories are employed to provide such data. Field chemists visit the site and collect samples, bringing them back to the laboratory for further testing or conducting the test at the site. Field chemists are also called on to install, maintain, and repair durable automatic testing equipment.

One such laboratory in Pennsylvania describes their field services: "Our team of field technicians undergoes extensive training in all aspects of sample collection including sampling for various types of drinking water, wastewater, industrial waste, pools, sludge and biosolids. Our highly qualified staff will ensure that your samples are collected, stored properly and transported according to all EPA requirements.… Field analysis capabilities include, but are not limited to, pH, chlorine, dissolved oxygen, conductivity, flow rate, and temperature. We maintain high levels of standards for calibration and equipment maintenance to ensure the most accurate results possible."

New opportunities are opening for entry-level field chemists as medical cannabis testing becomes necessary. Maintaining government regulations in the cannabis industry requires field chemists. One such job posting lists these qualifications:

- High school diploma or GED required with a least one year of college chemistry laboratory experience, or one year of analytical laboratory experience required
- Associates degree in a science field preferred
- 1+ years of experience
- Experience with HPLC, GC, LCMS, ICPMS
- Must be able to work in a teamwork oriented working environment
- Excellent computer skills in a Microsoft Windows environment, including Word, Excel and PowerPoint

Field chemists serve as gatekeepers for the regulation of many businesses and play an important role in community and environmental safety.

Sources: Suburban Testing Labs Retrieved April 4, 2020 from:https://www.suburbantestinglabs.com/lab-services/field-sampling-analysis.html; Chemist Job Posting. Retrieved April 4, 2020 from:https://cannabizteam.com/

Concept Summary

6.1 Observed Properties of Matter

Learning Objective: Can you do calculations based on the property of density?

- Matter in the solid, liquid, or gaseous state shows differences in physical properties.
- Such properties are density, shape, compressibility, and thermal expansion.

6.2 The Kinetic Molecular Theory of Matter

Learning Objective: Can you demonstrate an understanding of the kinetic molecular theory of matter?

- Much of the behavior of matter in different states can be explained by the kinetic molecular theory.
- It states that all matter is composed of tiny molecules that are in constant motion and are attracted or repelled by each other.

6.3 The Solid State

Learning Objective: Can you use the kinetic molecular theory to explain and compare the properties of matter in different states?

- In the solid state, cohesive forces between particles of matter are stronger than disruptive forces.
- As a result, the particles of solids are held in rigid three-dimensional lattices in which the particles' kinetic energy takes the form of vibrations about each lattice site.

6.4 The Liquid State

Learning Objective: Can you use the kinetic molecular theory to explain and compare the properties of matter in different states?

- In the liquid state, cohesive forces between particles slightly dominate disruptive forces.
- As a result, particles of liquids are randomly arranged but relatively close to each other and are in constant random motion, sliding freely over each other but without enough kinetic energy to become separated.

6.5 The Gaseous State

Learning Objective: Can you use the kinetic molecular theory to explain and compare the properties of matter in different states?

- In the gaseous state, disruptive forces dominate and particles move randomly, essentially independent of each other.
- Under ordinary pressure, the particles are separated from each other by relatively large distances except when they collide.

6.6 The Gas Laws

Learning Objective: Can you do calculations to convert pressure and temperature values into various units?

- Mathematical relationships called gas laws describe the observed behavior of gases when they are mixed, subjected to pressure or temperature changes, or allowed to diffuse.
- When these relationships are used, it is necessary to express the volume and pressure in consistent units and the temperature in kelvins.

6.7 Pressure, Temperature, and Volume Relationships

Learning Objective: Can you do calculations based on Boyle's law, Charles's law, and the combined gas law?

- Gas laws discovered by Robert Boyle and Jacques Charles led to the development of the combined gas law.
- This law allows calculations to be made that relate temperature, pressure, and volume changes for gases.

6.8 The Ideal Gas Law

Learning Objective: Can you do calculations based on the ideal gas law?

- The application of a gas law discovered by Amadeo Avogadro to the combined gas law led to the ideal gas law.
- It allows calculations to be made that account for the number of moles of gas in a sample.

6.9 Dalton's Law

Learning Objective: Can you do calculations based on Dalton's law?

- John Dalton discovered experimentally that the total pressure exerted by a mixture of gases is equal to the sum of the partial pressure of the individual gases in the mixture.

6.10 Graham's Law

Learning Objective: Can you do calculations based on Graham's law?

- Thomas Graham proposed a relationship that mathematically relates the rate of effusion or diffusion of a gas to the mass of the gas molecules.

6.11 Changes in State

Learning Objective: Can you classify changes in state as exothermic or endothermic?

- Most matter can be changed from one state to another by heating, cooling, or changing pressure.
- State changes that give up heat are called exothermic.
- Those that absorb heat are called endothermic.

6.12 Evaporation and Vapor Pressure

Learning Objective: Can you demonstrate an understanding of the concepts of vapor pressure and evaporation?

- The evaporation of a liquid is an endothermic process and as a result is involved in many cooling processes.
- In a closed container, evaporation takes place only until the rate of escape of molecules from the liquid is equal to the rate at which they return to the liquid.
- The pressure exerted by the vapor, which is in equilibrium with the liquid, is called the vapor pressure of the liquid.
- Liquid vapor pressures increase as the liquid temperature increases.

6.13 Boiling and the Boiling Point

Learning Objective: Can you demonstrate an understanding of the process of boiling and the concept of boiling point?

- At the boiling point of a liquid, its vapor pressure equals the prevailing atmospheric pressure.
- Bubbles of vapor form within the liquid and rise to the surface as the liquid boils.
- The boiling point of a liquid changes as the prevailing atmospheric pressure changes.

6.14 Sublimation and Melting

Learning Objective: Can you demonstrate an understanding of the processes of sublimation and melting?

- Solids, like liquids, have vapor pressures that increase with temperature.
- Some solids have vapor pressures high enough to allow them to change to vapor without first becoming a liquid, a process called sublimation.
- Most solids change to the liquid state before they change to the vapor state.
- The temperature at which solids change to liquids is called the melting point.

6.15 Energy and the States of Matter

Learning Objective: Can you do calculations based on energy changes that accompany heating, cooling, or changing the state of a substance?

- Energy is absorbed or released when matter is changed in temperature or changed from one state to another.
- The amount of heat energy required to produce temperature changes is called the specific heat of the matter involved.
- For phase changes, the amount of heat required is called the heat of fusion, or of vaporization.

Key Terms and Concepts

Absolute zero (6.6)
Avogadro's law (6.8)
Boiling point (6.13)
Boyle's law (6.7)
Charles's law (6.7)
Cohesive forces (6.2)
Combined gas law (6.7)
Compressibility (6.1)
Condensation (6.12)
Dalton's law of partial pressures (6.9)
Decomposition (6.14)
Diffusion (6.10)
Disruptive forces (6.2)
Effusion (6.10)
Evaporation or vaporization (6.12)
Gas laws (6.6)
Graham's law (6.10)
Heat of fusion (6.15)
Heat of vaporization (6.15)
Ideal gas law (6.8)
Kinetic energy (6.2)
Melting point (6.14)
Normal or standard boiling point (6.13)
Partial pressure (6.9)
Potential energy (6.2)
Pressure (6.6)
Shape (6.1)
Specific heat (6.15)
Standard atmosphere (6.6)
Standard conditions (STP) (6.8)
Sublimation (6.14)
Thermal expansion (6.1)
Torr (6.6)
Universal gas constant (6.8)
Vapor pressure (6.12)

Key Equations

1. Calculation of volume from mass and density (**Section 6.1**):	$V = \frac{m}{d}$	Equation 6.1
2. Calculation of kinetic energy of particles in motion (**Section 6.2**):	$\text{K.E.} = \frac{1}{2}mv^2$	Equation 6.2
3. Boyle's law (**Section 6.7**):	$P = \frac{k}{V}$ $PV = k$	Equation 6.3 Equation 6.4
4. Charles's law (**Section 6.7**):	$\frac{V}{T} = k'$ $V = k'T$	Equation 6.5 Equation 6.6
5. Combined gas law (**Section 6.7**):	$\frac{PV}{T} = k''$ $\frac{P_iV_i}{T_i} = \frac{P_fV_f}{T_f}$	Equation 6.7 Equation 6.8
6. Ideal gas law (**Section 6.8**):	$PV = nRT$	Equation 6.9
7. Molecular weight determination (**Section 6.8**):	$PV = \frac{mRT}{\text{MW}}$	Equation 6.11
8. Dalton's law (**Section 6.9**):	$P_t = P_\triangle + P_\bigcirc + P_\square$	Equation 6.12
9. Graham's law of effusion (**Section 6.10**):	$\frac{\text{effusion rate } A}{\text{effusion rate } B} = \sqrt{\frac{\text{molecular mass of } B}{\text{molecular mass of } A}}$	Equation 6.13
10. Heat calculation (**Section 6.15**):	Heat = (sample mass)(specific heat)(temp. change)	Equation 6.14

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Observed Properties of Matter (Section 6.1)

6.1 Calculate the volume of 125 g of the following liquids:

- **a.** Acetone ($d = 0.792$ g/mL)
- **b.** Olive oil ($d = 0.918$ g/mL)
- **c.** Chloroform ($d = 1.49$ g/mL)

6.2 Calculate the volume of 125 g of the following liquids:

- **a.** Sea water ($d = 1.03$ g/mL)
- **b.** Methyl alcohol ($d = 0.792$ g/mL)
- **c.** Concentrated sulfuric acid ($d = 1.84$ g/mL)

6.3 Copper metal has a density of 8.92 g/cm^3 at 20.0°C and 8.83 g/cm^3 at 100.0°C. Calculate the change in volume that occurs when a 10.0-cm^3 piece of copper is heated from 20.0°C to 100.0°C.

6.4 Liquid water has a density of 1.00 g/mL at 10.0°C and 0.996 g/mL at 30.0°C. Calculate the change in volume that occurs when 500. mL of water is heated from 10.0°C to 30.0°C.

6.5 Gallium metal melts at 29.8°C. At the melting point, the density of the solid is 5.90 g/mL, and that of the liquid is 6.10 g/mL.

- **a.** Does solid gallium expand or contract when it is melted? Explain.
- **b.** What is the change in volume when 5.00 mL (cm^3) of solid gallium is melted?

6.6 To study the metabolism of runners, a researcher collected exhaled air from runners during a marathon. A runner fills a rubber balloon with 1.50 L of exhaled air at a temperature of 0.00°C and a pressure of 1.00 atm. The density of the exhaled air under these conditions is 1.56 g/L.

- **a.** Will the density of the exhaled air increase or decrease when the balloon is heated?
- **b.** At 50.0°C, the balloon has a volume of 1.78 L. Calculate the exhaled air density at this temperature.

The Kinetic Molecular Theory of Matter (Section 6.2)

6.7 Describe the changes in form of energy (kinetic changes to potential, etc.) that occur for the energy of a rock dropped to the ground from a cliff. What form or forms do you suppose the energy takes when the rock hits the ground?

6.8 Suppose a toy ball is thrown into the air such that it goes straight up, then falls and is caught by the person who threw it. Describe the changes in the form of energy that occur for the ball from the time it is thrown until it is caught.

6.9 Suppose a 180-lb (81.8-kg) halfback running at a speed of 8.0 m/s collides head-on with a 260-lb (118.2-kg) tackle running at 3.0 m/s. Which one will be pushed back? That is, which one has less kinetic energy? If you're not familiar with football, check with someone who is for definition of terms.

6.10 Nitrous oxide (N_2O, M.W. = 44.0 u) and sevoflurane ($C_4H_3F_7O$, M.W. = 200.1 u) are commonly used outpatient inhalation anesthesias. At 25.0°C, nitrous oxide molecules have an average velocity of 3.78×10^4 cm/s and sevoflurane molecules have an average velocity of 1.77×10^4 cm/s. Calculate the kinetic energy of each type of molecule at 25.0°C and determine whether they are significantly different. Express molecular masses in u for this calculation.

6.11 Which have the greater kinetic energy, hydrogen molecules traveling with a velocity of $2v$, or helium molecules traveling with a velocity of v? Express molecular masses in u.

The Solid, Liquid, and Gaseous States (Sections 6.3–6.5)

6.12 Explain each of the following observations using the kinetic molecular theory of matter:

- **a.** A liquid takes the shape, but not necessarily the volume, of its container.
- **b.** Solids and liquids are practically incompressible.
- **c.** A gas always exerts uniform pressure on all walls of its container.

6.13 Explain each of the following observations using the kinetic molecular theory of matter:

- **a.** Gases have low densities.
- **b.** The densities of a substance in the solid and liquid states are nearly identical.
- **c.** Solids, liquids, and gases all expand when heated.

6.14 Discuss differences in kinetic and potential energy of the constituent particles for a substance in the solid, liquid, and gaseous states.

6.15 The following statements are best associated with the solid, liquid, or gaseous states of matter. Match the statements to the appropriate state of matter.

- **a.** This state is characterized by the lowest density of the three.
- **b.** This state is characterized by an indefinite shape and a high density.
- **c.** In this state, disruptive forces prevail over cohesive forces.
- **d.** In this state, cohesive forces are most dominant.

6.16 The following statements are best associated with the solid, liquid, or gaseous state of matter. Match each statement to the appropriate state of matter.

- **a.** Temperature changes influence the volume of this state substantially.
- **b.** In this state, constituent particles are less free to move about than in other states.
- **c.** Pressure changes influence the volume of this state more than that of the other two states.
- **d.** This state is characterized by an indefinite shape and a low density.

The Gas Laws (Section 6.6)

6.17 What is a gas law?

6.18 A weather reporter on TV reports the barometer pressure as 28.6 inches of mercury. Calculate this pressure in the following units:

- **a.** atm
- **b.** torr
- **c.** psi
- **d.** bars

6.19 The pressure of a gas sample is recorded as 585 torr. Calculate this pressure in the following units:

- **a.** atm
- **b.** in. Hg
- **c.** psi
- **d.** bars

6.20 An engineer reads the pressure gauge of a boiler as 210 psi. Calculate this pressure in the following units:

- **a.** atm
- **b.** bars
- **c.** mmHg
- **d.** in. Hg

6.21 An anesthesiologist reads the pressure of an anesthesia administered during an operation as 16.8 cmHg. Calculate this pressure in the following units:

- **a.** atm
- **b.** mmHg
- **c.** torr
- **d.** psi

6.22 Convert each of the following temperatures from the unit given to the unit indicated:

- **a.** Liquid helium used to cool MRI magnets has a boiling point of −268.9°C. Convert this to Kelvins.
- **b.** The freezing point of liquid hydrogen, 14.1 K, to degrees Celsius.
- **c.** An inhaled anesthesia boils at 63.7°C, at which point it can be inhaled. Convert this to Kelvins.

6.23 Convert each of the following temperatures from the unit given to the unit indicated:

- **a.** The melting point of gold, 1337.4 K, to degrees Celsius.
- **b.** The melting point of tungsten, 3410°C, to kelvins.
- **c.** The melting point of tin, 505 K, to degrees Celsius.

Pressure, Temperature, and Volume Relationships (Section 6.7)

6.24 Use the combined gas law (Equation 6.8) to calculate the unknown quantity for each gas sample described in the following table.

	Sample		
	A	**B**	**C**
P_i	1.50 atm	2.35 atm	9.86 atm
V_i	2.00 L	1.97 L	11.7 L
T_i	300. K	293 K	500. K
P_f	?	1.09 atm	5.14 atm
V_f	3.00 L	?	9.90 L
T_f	450. K	310 K	?

6.25 A 200.-mL sample of oxygen gas is collected at 26.0°C and a pressure of 690. torr. What volume will the gas occupy at STP (0°C and 760 torr)?

6.26 A 200.-mL sample of nitrogen gas is collected at 45.0°C and a pressure of 610. torr. What volume will the gas occupy at STP (0°C and 760 torr)?

6.27 A 3.00-L sample of helium at 0.00°C and 1.00 atm is compressed into a 0.50-L cylinder. What pressure will the gas exert in the cylinder at 50.°C?

6.28 A 2.50-L sample of neon at 0.00°C and 1.00 atm is compressed into a 0.75-L cylinder. What pressure will the gas exert in the cylinder at 30.°C?

6.29 What volume (in liters) of air measured at 1.00 atm would have to be put into a bicycle tire with a 1.00-L volume if the pressure in the bike tire is to be 65.0 psi? Assume the temperature of the gas remains constant.

6.30 What volume (in liters) of air measured at 1.00 atm would have to be put into a car tire with a volume of 14.5 L if the pressure in the car tire is to be 32.0 psi? Assume the temperature of the gas remains constant.

6.31 A patient is diagnosed with a 1000-mL pneumothorax (air trapped between the lung and chest wall, causing the lung to collapse) at sea level (air pressure, 760 torr). If the patient is to be transported by helicopter at an altitude of 5000 ft (air pressure, 620 torr), what will the size of the pneumothorax be during the transport?

6.32 A 5.0 L portable oxygen tank used by people with respiratory ailments, is pressurized to 2000 psi with oxygen. Assuming no temperature change, how many liters of oxygen are available to the patient at 14.0 psi?

6.33 A scuba diving regulator is designed to reduce the pressure of the air in a scuba tank to the pressure that the diver is experiencing, thus allowing the diver to breathe. If the diver breathes in 300. mL of air from the tank through the regulator, which is at 4°C. What is the volume of the air in her lungs which are at 37°C? Assume constant pressure.

6.34 A 3.8 L sample of gas at 1.0 atm and 20.°C is heated to 85°C. Calculate the gas volume in liters at the higher temperature if the pressure remains constant at 1.0 atm.

6.35 If an individual draws a breath of 1.00 L at 16°C, what is the new volume of air as it warms to 37°C? Assume the pressure and amount of gas remains constant.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

6.36 What volume of gas in liters at 120.°C must be cooled to 40.°C if the gas volume at constant pressure and 40.°C is to be 2.0 L?

6.37 A person undergoing a laparoscopic abdominal surgery procedure will have their abdominal cavity inflated with carbon dioxide for the procedure. If 180 mL of CO_2 at 2500. torr and 20°C is put into the abdominal cavity of the patient, which exerts 940 torr of pressure on the gas at a temperature of 37°C, what is the new volume of the insufflated carbon dioxide?

6.38 When stressed, people sometimes swallow air, which causes them to burp. A researcher is studying the relationship between volume of burps and stress. Your diaphragm detects pressure as discomfort at 210.0 kPa (body temperature is 37°C), leading to a burp. If you feel discomfort and burp into the researcher's balloon, the balloon slightly inflates to 7.64 mL at 94.6 kPa and 22°C. What volume did the burp occupy in your stomach?

6.39 A 6.25 L tank contains the inhalation anesthesia sevoflurane at 3.25 atm and 10.0°C. It is to be given to a patient at 0.250 atm of pressure and 37°C. What volume of sevoflurane (in liters) will be available to the patient?

6.40 A helium balloon was partially filled with 8.00×10^3 ft^3 of helium when the atmospheric pressure was 0.98 atm and the temperature was 23°C. The balloon rose to an altitude where the atmospheric pressure was 400. torr and the temperature was 5.3°C. What volume did the helium occupy at this altitude?

6.41 You have a 1.50 L balloon full of air at 30.°C. To what Celsius temperature would you have to heat the balloon to double its volume if the pressure remained unchanged?

6.42 An oyster diver completely fills her lungs with 4.00 L of air at the ocean's surface (1.00 atm pressure). She descends to a depth of 20 m, where the water exerts 3.00 atm of pressure on her. What is the volume of air in her lungs now, assuming no temperature change?

6.43 What minimum pressure would a 250.-mL aerosol can have to withstand if it were to contain 2.00 L of gas measured at 700. torr? Assume constant temperature.

6.44 A 2.00-L sample of nitrogen gas at 760. torr and 0.0°C weighs 2.50 g. The pressure on the gas is increased to 4.00 atm at 0.0°C. Calculate the gas density at the new pressure in g/L.

The Ideal Gas Law (Section 6.8)

6.45 Use the ideal gas law and calculate the following:

- **a.** The pressure exerted by 2.00 mol of oxygen confined to a volume of 400. mL at 20.0°C.
- **b.** The volume of hydrogen gas in a steel cylinder if 0.525 mol of the gas exerts a pressure of 3.00 atm at a temperature of 15.0°C.
- **c.** The temperature (in degrees Celsius) of a nitrogen gas sample that has a volume of 2.25 L and a pressure of 300. torr and contains 0.100 mol.

6.46 Use the ideal gas law and calculate the following:

- **a.** The number of moles of argon in a gas sample that occupies a volume of 400. mL at a temperature of 90.0°C and has a pressure of 735 torr.
- **b.** The pressure in atm exerted by 0.750 mol of hydrogen gas confined to a volume of 2.60 L at 50.0°C.
- **c.** The volume in liters of a tank of nitrogen if 1.50 mol of the gas exerts a pressure of 4.32 atm at 20.0°C.

6.47 Suppose 0.156 mol of SO_2 gas is compressed into a 0.750 L steel cylinder at a temperature of 27°C. What pressure in atmospheres is exerted by the gas?

6.48 Suppose 10.0 g of SO_2 gas is compressed into a 1.25 L steel cylinder at a temperature of 38.0°C. What pressure in atm is exerted by the gas?

6.49 Calculate the volume occupied by 8.75 g of oxygen gas (O_2) at a pressure of 0.890 atm and a temperature of 35.0°C.

6.50 The pressure gauge of a steel cylinder of methane gas (CH_4) reads 400. psi. The cylinder has a volume of 1.50 L and is at a temperature of 30.0°C. How many grams of methane does the cylinder contain?

6.51 Suppose 12.0 g of dry ice (solid CO_2) was placed in an empty 400.-mL steel cylinder. What pressure would develop if all the solid sublimed at a temperature of 35.0°C?

6.52 An experimental chamber has a volume of 60. L. How many moles of oxygen gas will be required to fill the chamber at STP?

6.53 How many molecules of nitrogen gas (N_2) are present in a sample that fills a 10.0 L tank at STP?

6.54 A sample of gaseous inhalation anesthesia desflurane has a mass of 29.7 g and occupies a volume of 3.96 L at STP. What is the molecular weight of desflurane?

6.55 If an individual draws a breath of 1.00 L at 1.00 atm and 35°C, what mass of air is contained in the breath? Assume that air has an average molar mass of 28.6 g/mol for air.

6.56 A sample of gas weighs 0.176 g and has a volume of 114.0 mL at a pressure and temperature of 640. torr and 20.°C. Determine the molecular weight of the gas, and identify it as CO, CO_2, or O_2.

6.57 A 2.00-g sample of gas has a volume of 1.12 L at STP. Calculate its molecular weight and identify it as He, Ne, or Ar.

Dalton's Law (Section 6.9)

6.58 Heliox is a supplemental breathing gas mixture of helium and oxygen that is used to alleviate symptoms of severe asthma, emphysema, and COPD (chronic obstructive pulmonary disease). The total pressure in the tank is 2100 torr. The pressure exerted by the helium is 1680 torr. What is the partial pressure in torr of the oxygen in the mixture? What is the percent composition of this mixture (percent helium/percent oxygen)?

6.59 A 250-mL sample of oxygen gas is collected by water displacement. As a result, the oxygen is saturated with water vapor. The partial pressure of water vapor at the prevailing temperature is 22 torr. Calculate the partial pressure of the oxygen if the total pressure of the sample is 720. torr.

Graham's Law (Section 6.10)

6.60 Hydrogen gas (H_2) is found to diffuse approximately four times as fast as oxygen gas (O_2). Using this information, determine how the masses of hydrogen molecules and oxygen molecules compare. How do they compare based on information in the periodic table?

6.61 Two common inhalation anesthetics are sevoflurane and desflurane. The mass of a sevoflurane molecule is 200.1 g and the mass of a desflurane molecule is 168.0 g. Compare the rates at which these gases will diffuse.

6.62 Two identical rubber balloons were filled with gas—one with helium and the other with nitrogen. After a time, it was noted that one of the balloons appeared to be going "flat." Which one do you think it was? Explain.

6.63 Assume the balloon in Exercise 6.62 that went flat first showed signs of "flatness" 10 hours after it was filled. How long would it take for the other balloon to begin to show signs of going flat?

Changes in State (Section 6.11)

6.64 Classify each of the following processes as endothermic or exothermic:

a. condensation

b. liquefaction

c. boiling

6.65 Classify each of the following processes as endothermic or exothermic:

a. freezing

b. sublimation

c. vaporization

6.66 An autoclave is used to sterilize surgical equipment. In it, water is heated to become high-pressure steam. High temperature and high-pressure steam effectively inactivates bacteria and viruses. At the end of the sterilization cycle, the steam is cooled back to liquid water and ambient pressure before the autoclave is opened. Name the changes of state that occurred to the water and identify them as endothermic or exothermic.

Evaporation and Vapor Pressure (Section 6.12)

6.67 The following are all nonpolar liquid hydrocarbon compounds derived from petroleum: butane (C_4H_{10}), pentane (C_5H_{12}), hexane (C_6H_{14}), and heptane (C_7H_{16}). Arrange these compounds in order of increasing vapor pressure (lowest first, highest last) and explain how you arrived at your answer.

6.68 Methylene chloride (CH_2Cl_2) was used at one time as a local anesthetic by dentists. It was sprayed onto the area to be anesthetized. Propose an explanation for how it worked.

6.69 Suppose a drop of methyl ether (C_2H_6O) was put on the back of one of your hands and a drop of ethyl ether ($C_4H_{10}O$) was put on your other hand. Propose a way you could tell which compound was which without smelling them.

Boiling and the Boiling Point (Section 6.13)

6.70 Each of two glass containers contains a clear, colorless, odorless liquid that has been heated until it is boiling. One liquid is water (H_2O) and the other is ethylene glycol ($C_2H_6O_2$). Explain how you could make one measurement of each boiling liquid, using the same device, and tell which liquid was which.

6.71 Autoclaves are used to sterilize equipment in hospitals. They typically operate at a pressure of 15 psi above ambient pressure. Autoclaves also require water in the form of steam to operate. Explain what happens to the boiling point of water under 15 psi pressure. The normal boiling point of water is 100°C. What would the temperature inside an autoclave be?

6.72 Suppose you were on top of Mount Everest and wanted to cook a potato as quickly as possible. You left your microwave oven at home, so you could either boil the potato in water or throw it into a campfire. Explain which method you would use and why.

Sublimation and Melting (Section 6.14)

6.73 In a clinical procedure, a pathologist may choose to put tissue samples that need to remain frozen and dry in a dry ice (solid CO_2) cooler rather than a regular water ice cooler. Why?

6.74 Solid iodine readily sublimes without melting when moderately heated. The hot vapor will condense back to the solid state when it cools. Describe a method that could be used to obtain pure solid iodine from a mixture of solid iodine and sand. Explain your reasoning.

6.75 A mixture was made of pure water and ice. The mixture was allowed to come to a constant temperature of 0.0°C, the melting point of solid water. The vapor pressure of the water was measured and found to be 4.58 torr. What is the vapor pressure of the ice in torr? Explain your answer.

Energy and the States of Matter (Section 6.15)

6.76 Using the specific heat data of **Table 6.7**, calculate the amount of heat (in calories) needed to increase the temperature of the following:

a. 50. g of aluminum from 25°C to 55°C

b. 2.50×10^3 g of ethylene glycol from 80.°C to 85°C

c. 500. g of steam from 110.°C to 120.°C

6.77 Using the specific heat data of **Table 6.7**, calculate the amount of heat (in calories) needed to increase the temperature of the following:

a. 210 g of copper from 40.°C to 95.°C

b. 150 g of mercury from 120.°C to 300.°C

c. 2.50×10^3 g of helium gas from 250.°C to 900.°C

6.78 For solar energy to be effective, collected heat must be stored for use during periods of decreased sunshine. One proposal suggests that heat can be stored by melting solids that, upon solidification, would release the heat. Calculate the heat that could be stored by melting 1000. kg of each of the following solids. (*Note*: The water in each formula is included in the molecular weight.)

a. Calcium chloride ($CaCl_2 \cdot 6H_2O$): melting point = 30.2°C, heat of fusion = 40.7 cal/g

b. Lithium nitrate ($LiNO_3 \cdot 3H_2O$): melting point = 29.9°C, heat of fusion = 70.7 cal/g

c. Sodium sulfate ($Na_2SO_4 \cdot 10H_2O$): melting point = 32.4°C, heat of fusion = 57.1 cal/g

6.79* Why wouldn't a solid such as K_2SO_4 (melting point = 1069°C, heat of fusion = 50.3 cal/g) be suitable for use in a solar heat storage system? (See Exercise 6.78.)

6.80 Refrigerators and freezers are an integral part of maintaining human health both at home and in hospitals. Liquid Freon (CCL_2F_2) was once used as a refrigerant. It was circulated inside the cooling coils of older refrigerators or freezers. As it vaporized, it absorbed heat. How much heat could be removed by 2.00 kg of Freon as it vaporized inside the coils of a refrigerator? The heat of vaporization of Freon is 38.6 cal/g.

6.81 Calculate the total amount of heat needed to change 0.500 kg of ice at −10.°C into 0.500 kg of steam at 120.°C. Do this by calculating the heat required for each of the following steps and adding to get the total:

Step 1. Ice (−10.°C) → ice (0.°C)

Step 2. Ice (0.°C) → water (0.°C)

Step 3. Water (0.°C) → water (100.°C)

Step 4. Water (100.°C) → steam (100.°C)

Step 5. Steam (100.°C) → steam (120.°C)

Additional Exercises

6.82 What is the density of the gaseous anesthesia nitrous oxide (N_2O) in g/mL at STP?

6.83 Explosives react very rapidly and produce large quantities of heat and gaseous products. When nitroglycerine explodes, several gases are produced:

$$4C_3H_5O_9N_3(\ell) \rightarrow 12CO_2(g) + O_2(g) + 6N_2(g) + 10H_2O(g)$$

Suppose 11 g of nitroglycerine was sealed inside a 1.0-L soda bottle and detonated. Assume the bottle would not break, and the temperature immediately after detonation was 750 K. Calculate the pressure of the gases inside the bottle in atmospheres.

6.84 How many liters of oxygen gas, O_2, will it take to completely react with 2.31 L of hydrogen gas, H_2, to produce water? Assume both gases are at the same pressure and temperature. What type of reaction is this?

6.85 Review **Table 6.4**; then propose an explanation for the fact that hydrogen bonding decreases the vapor pressure of liquids made up of molecules with similar molecular weights.

6.86 Some people say they have a hard time breathing on top of a tall mountain because there is less oxygen in the air they breathe. Is this a true statement? Explain your answer.

Chemistry for Thought

6.87 Sevoflurane, an inhalation anesthesia, has a boiling point of 58.5°C. As the liquid is heated past the boiling point, it changes to gas. Explain this in terms of the effect of temperature on cohesive and disruptive forces.

6.88 Explain how a hot-air balloon works in terms of gas densities.

6.89 Which of the following gases would you expect to behave most ideally: He, Ar, or HCl? Explain.

6.90 Refer to **Figure 6.10** and do the calculation. When a gas is heated, it expands. Explain how the gas in a hot-air balloon remains at constant pressure as the gas is heated. Hot-air balloons do *not* stretch.

6.91 Refer to **Figure 6.11** and answer the question. Would a quart bottle full of gas actually contain the number of moles you calculated? Explain.

6.92 Refer to **Figure 6.13** and answer the question. Propose an explanation for your answer in terms of the distances between molecules in rubber and plastic.

6.93 Water is sometimes made safe to drink by boiling. Explain why this might not work if you attempted to do it in an open pan on the summit of Mount Everest.

6.94 Suppose a sample of water was heated to the boiling point in a glass beaker, using a single burner. What would happen to the temperature of the boiling water if a second burner was added to help with the heating? Explain.

6.95 Suppose you put four 250 mL bottles of water into an ice chest filled with crushed ice. If the bottles were initially at a temperature of 23°C, calculate the number of grams of ice that would have to melt in order to cool the water in the bottles to 5°C. Assume the density of water is 1.00 g/mL.

7 Solutions and Colloids

Elnur/Shutterstock.com

Health Career Focus

PERSONAL CARE PRODUCT DEVELOPER

"Lotions and potions." That's what I say when someone asks, "What kind of work are you in?" For as long as I can remember, I've loved cosmetics—shampoos, makeup, lotions, creams, and oils. To meet my approval, a product must smell amazing, contain natural botanicals and no animal products, should be environmentally conscientious, and promote overall health.

By poring over product catalogs, I discovered the fascinating career of "product formulation." Eventually, I landed a job as an assistant developer at a nutritional supplement laboratory. Not only must I know chemistry to understand active ingredients, but I must also understand the product bases as well. Understanding emulsification, suspension, solutions, and colloids in order to control the smoothness, fluffiness, thickness, or silkiness of a product is critical.

Every product I develop solves a complex puzzle addressing multiple questions. I love when all the parts come together—when a client opens a bottle, smells the product, and can't wait to go home and try it.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Classify mixtures as solutions or nonsolutions based on their appearance. **(Section 7.1)**
2. Demonstrate your understanding of terms related to the solubility of solutes in solution. **(Section 7.2)**
3. Predict in a general way the solubilities of solutes in solvents on the basis of molecular polarity. **(Section 7.3)**
4. Calculate solution concentrations in units of molarity, weight/weight percent, weight/volume percent, and volume/volume percent. **(Section 7.4)**

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

5 Describe how to prepare solutions of specific concentration using pure solutes and solvent, or solutions of greater concentration than the one desired. **(Section 7.5)**

6 Do stoichiometric calculations based on solution concentrations. **(Section 7.6)**

7 Do calculations based on the colligative solution properties of boiling point, freezing point, and osmotic pressure. **(Section 7.7)**

8 Describe the characteristics of colloids. **(Section 7.8)**

9 Describe the process of dialysis, and compare it to the process of osmosis. **(Section 7.9)**

EARLIER, homogeneous matter was classified into two categories—pure substances and mixtures (see **Figure 1.8**). Since then, the discussion has been limited to pure substances. We now look at homogeneous mixtures called solutions and their distant relatives, colloidal suspensions.

Solutions and colloidal suspensions are very important in our world. They bring nutrients to the cells of our bodies and carry away waste products. The ocean is a solution of water, sodium chloride, and many other substances (even gold). Many chemical reactions take place in solution—including most of those discussed in this book.

solution A homogeneous mixture of two or more substances in which the components are present as atoms, molecules, or ions.

solvent The substance present in a solution in the largest amount.

solute One or more substances present in a solution in amounts less than that of the solvent.

dissolving A term used to describe the process of solution formation when one or more solutes are dispersed in a solvent to form a homogeneous mixture.

7.1 Physical States of Solutions

Learning Objective 1 Classify mixtures as solutions or nonsolutions based on their appearance.

Solutions are homogeneous mixtures of two or more substances in which the components are present as atoms, molecules, or ions. These uniformly distributed particles are too small to reflect light, and as a result liquid solutions are transparent (clear); light passes through them. In addition, some solutions are colored. The component particles are in constant motion (remember the kinetic theory, **Section 6.2**) and do not settle under the influence of gravity.

In most solutions, a larger amount of one substance is present compared to the other components. This most abundant substance in a solution is called the **solvent**, and any other components are called **solutes**. Most people normally think of solutions as liquids, but solutions in solid (see **Figure 7.1**) and gaseous forms are known as well. The state of a solution is often the same as the state of the solvent. This is illustrated in **Table 7.1**, which lists examples of solutions in various states. The original states of the solvents and solutes are given in parentheses. Solution formation takes place when one or more solutes **dissolve** in a solvent.

manx_in_the_world/E+/Getty Images

FIGURE 7.1 Stainless steel is a solid solution of several metals. It is used in the construction of surgical implants and instruments where corrosion resistance, reliability, and hygiene are of particular importance.

TABLE 7.1 Solutions in Various States

Solution	Solution State	Solvent	Solute
Salt water	Liquid	Water (liquid)	Sodium chloride (solid)
Alcoholic beverage	Liquid	Water (liquid)	Alcohol (liquid)
Carbonated water	Liquid	Water (liquid)	Carbon dioxide (gas)
Gold alloy (jewelry)	Solid	Gold (solid)	Copper (solid)
Gold amalgam	Solid	Gold (solid)	Mercury (liquid)
Hydrogen in palladium	Solid	Palladium (solid)	Hydrogen (gas)
Air	Gaseous	Nitrogen (gas)	Oxygen (gas)
Humid oxygen	Gaseous	Oxygen (gas)	Water (liquid)
Camphor in nitrogen	Gaseous	Nitrogen (gas)	Camphor (solid)

Example 7.1 Identifying Solution, Solvent, and Solutes

Identify the solvent and solute(s) in each of the following solutions:

a. A sample of natural gas contains 97% methane (CH_4), 1.5% ethane (C_2H_6), 1% carbon dioxide (CO_2), and 0.5% nitrogen (N_2).

b. The label on a bottle of Scotch whiskey says, among other things, 86 proof. This means the contents contain 43% ethyl alcohol (C_2H_5OH). Assume water to be the only other component.

c. The physiological saline solution used in hospitals contains 0.9 g NaCl for each 100 g water.

Solution

a. Methane is present in the largest amount; it is the solvent. All other components are solutes.

b. The whiskey is 43% alcohol and 57% water. Thus, water is the solvent and alcohol is the solute. The whiskey actually contains small amounts of many other components, which impart flavor and color. These components are also solutes.

c. Water is the component present in the larger amount and is therefore the solvent.

✔ **LEARNING CHECK 7.1** Identify the solvent and solute(s) in the following solutions:

a. White gold is a solid solution containing 58.3% gold, 17.0% copper, 7.7% zinc, and 17.0% nickel.

b. Clean, dry air contains about 78.1% nitrogen, 21.0% oxygen, 0.9% argon, and very small amounts of other gases.

7.2 Solubility

Learning Objective 2 Demonstrate your understanding of terms related to the solubility of solutes in solution.

A few experiments with water, sugar, cooking oil, and rubbing alcohol (isopropyl alcohol) illustrate some important concepts associated with solution formation. Imagine you have three drinking glasses, each containing 100 mL (100 g) of pure water.

You begin by adding small amounts of the other three substances to the glasses. The mixtures are stirred well, with results shown in **Figure 7.2(a)**. The sugar and alcohol form homogeneous mixtures (solutions) with the water, while the oil forms a two-layer (heterogeneous) mixture. **Soluble substances** such as the sugar and alcohol dissolve completely in the solvent and form solutions. **Insoluble substances** do not dissolve in the solvent. The term **immiscible** is used to describe a liquid solute that does not dissolve in a liquid solvent.

soluble substance A substance that dissolves to a significant extent in a solvent.

insoluble substance A substance that does not dissolve to a significant extent in a solvent.

immiscible A term used to describe liquids that are insoluble in each other.

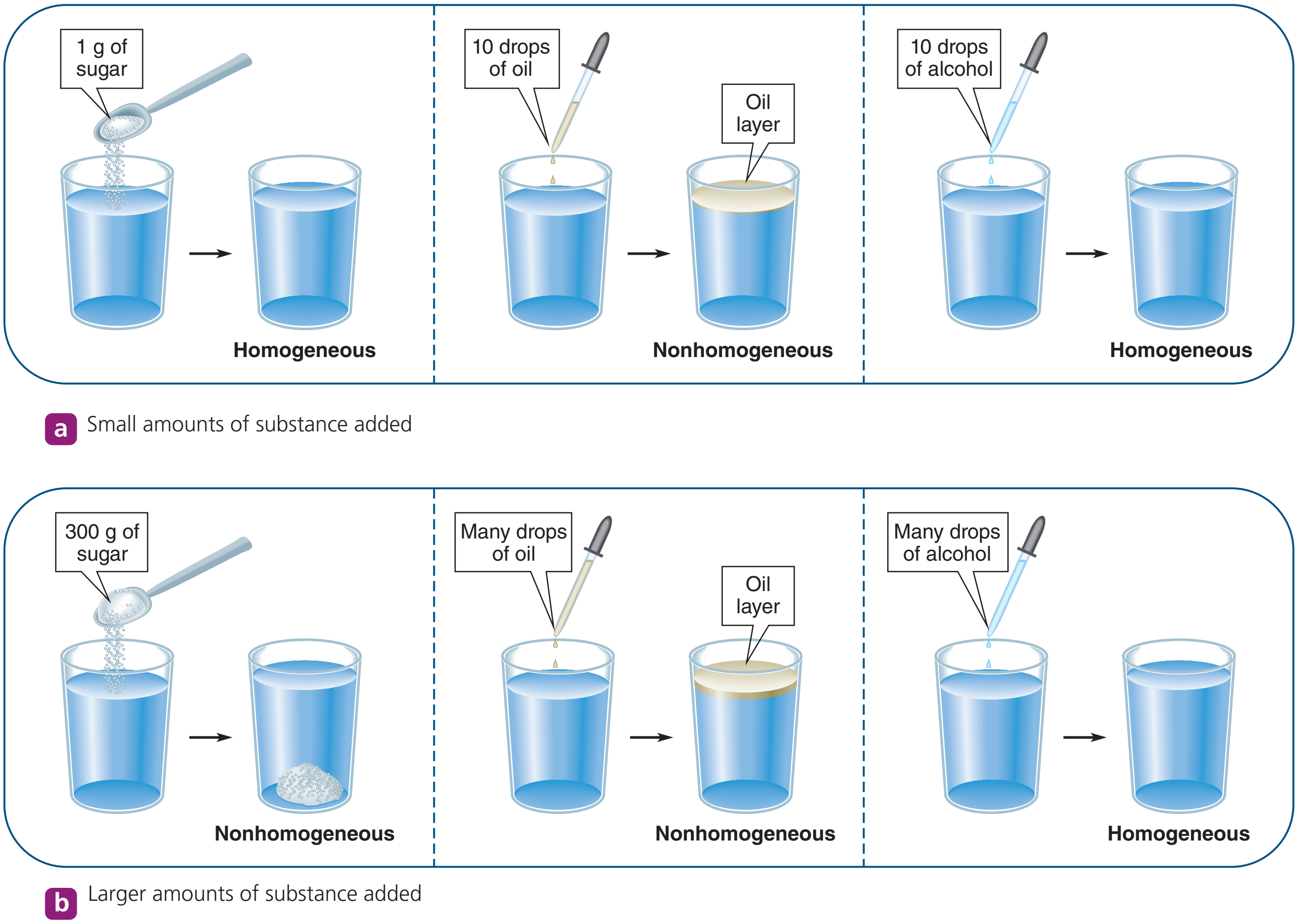

1 g of sugar
Homogeneous
10 drops of oil
Oil layer
Nonhomogeneous
10 drops of alcohol
Homogeneous
a
Small amounts of substance added
300 g of sugar
Nonhomogeneous
Many drops of oil
Oil layer
Nonhomogeneous
Many drops of alcohol
Homogeneous
b
Larger amounts of substance added

FIGURE 7.2 The homogeneity of solutions and mixtures of sugar (limited solubility), cooking oil (immiscible), and alcohol (completely soluble).

The experiments are continued by adding more sugar, alcohol, and oil to the water samples. This ultimately leads to the situation shown in **Figure 7.2(b)**. Regardless of the amount of alcohol added, a solution forms. In fact, other experiments could be done that show that water and isopropyl alcohol are completely soluble in each other and will mix in any proportion. Sugar behaves differently. About 204 g can be dissolved in the 100 mL of water (at 20°C), but any additional sugar simply sinks to the bottom of the glass and remains undissolved. Thus, the sugar has a solubility in water of 204 g/100 g H_2O. The term **solubility** refers to the maximum amount of solute that can be dissolved in a specific amount of solvent at a specific temperature. With the oil–water mixture, any additional oil simply floats on the surface of the water along with the oil added initially.

solubility The maximum amount of solute that can be dissolved in a specific amount of solvent under specific conditions of temperature and pressure.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The solubilities of a number of solutes in water are given in **Table 7.2**. The use of specific units, such as grams of solute per 100 g of water, makes it possible to compare solubilities precisely. However, such precision is often unnecessary, and when this is the case, the approximate terms defined in **Table 7.3** will be used.

TABLE 7.2 Examples of Solute Solubilities in Water (0°C)

Solute		Solubility
Name	**Formula**	**(g solute/100 g H_2O)**
Ammonium chloride	NH_4Cl	29.7
Ammonium nitrate	NH_4NO_3	118.3
Ammonium orthophosphate	$NH_4H_2PO_4$	22.7
Ammonium sulfate	$(NH_4)_2SO_4$	70.6
Calcium carbonate	$CaCO_3$	0.0012
Calcium chloride	$CaCl_2$	53.3
Calcium sulfate	$CaSO_4$	0.23
Potassium carbonate	K_2CO_3	101
Potassium chloride	KCl	29.2
Sodium bicarbonate	$NaHCO_3$	6.9
Sodium bromide	$NaBr$	111
Sodium carbonate	Na_2CO_3	7.1
Sodium chloride	$NaCl$	35.7
Sodium iodide	NaI	144.6
Ascorbic acid (vitamin C)	$C_6H_8O_6$	33
Ethyl alcohol	C_2H_5OH	∞[a]
Ethylene glycol (antifreeze)	$C_2H_4(OH)_2$	∞
Glycerin	$C_3H_5(OH)_3$	∞
Sucrose (table sugar)	$C_{12}H_{22}O_{11}$	179.2

[a] Soluble in all proportions.

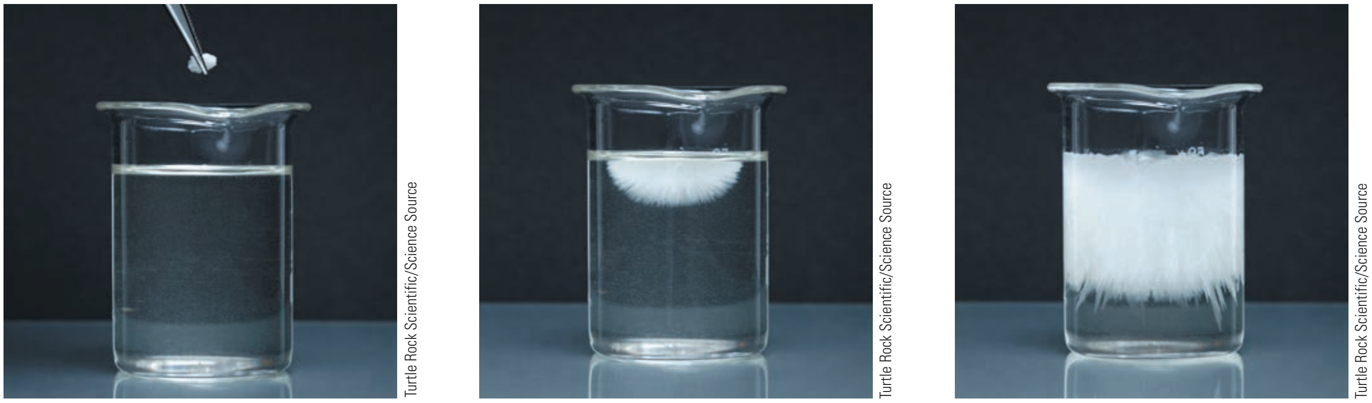
TABLE 7.3 Approximate Solubility Terms

Solute Solubility (g solute/ 100 g H_2O)	Solubility Term
Less than 0.1	Insoluble
0.1–1	Slightly soluble
1–10	Soluble
Greater than 10	Very soluble

saturated solution A solution that contains the maximum amount possible of dissolved solute in a stable situation under the prevailing conditions of temperature and pressure.

supersaturated solution An unstable solution that contains an amount of solute greater than the solute solubility under the prevailing conditions of temperature and pressure.

A solution in which the maximum amount of solute has been dissolved in a quantity of solvent is called a **saturated solution**. The final sugar solution described in the earlier experiments (204 g in 100 g H_2O) was a saturated solution. Solutions in which the amount of solute dissolved is greater than the solute solubility are called **supersaturated solutions**. Supersaturated solutions are usually prepared by forming a nearly saturated solution at a high temperature and then cooling the solution to a lower temperature at which the solubility is lower. Such solutions are not stable. The addition of a small amount of solid solute (or even a dust particle) will usually cause the excess solute to crystallize out of solution until the solution becomes saturated (see **Figure 7.3**). The temperature dependence of solute solubility is illustrated in **Figure 7.4**.


Turtle Rock Scientific/Science Source

Turtle Rock Scientific/Science Source

Turtle Rock Scientific/Science Source

1 A supersaturated solution just before adding a small seed crystal.

2 Rapid crystallization begins on the seed crystal.

3 The excess solute has all crystallized, leaving behind a saturated solution.

FIGURE 7.3 Crystallization converts a supersaturated solution to a saturated solution.

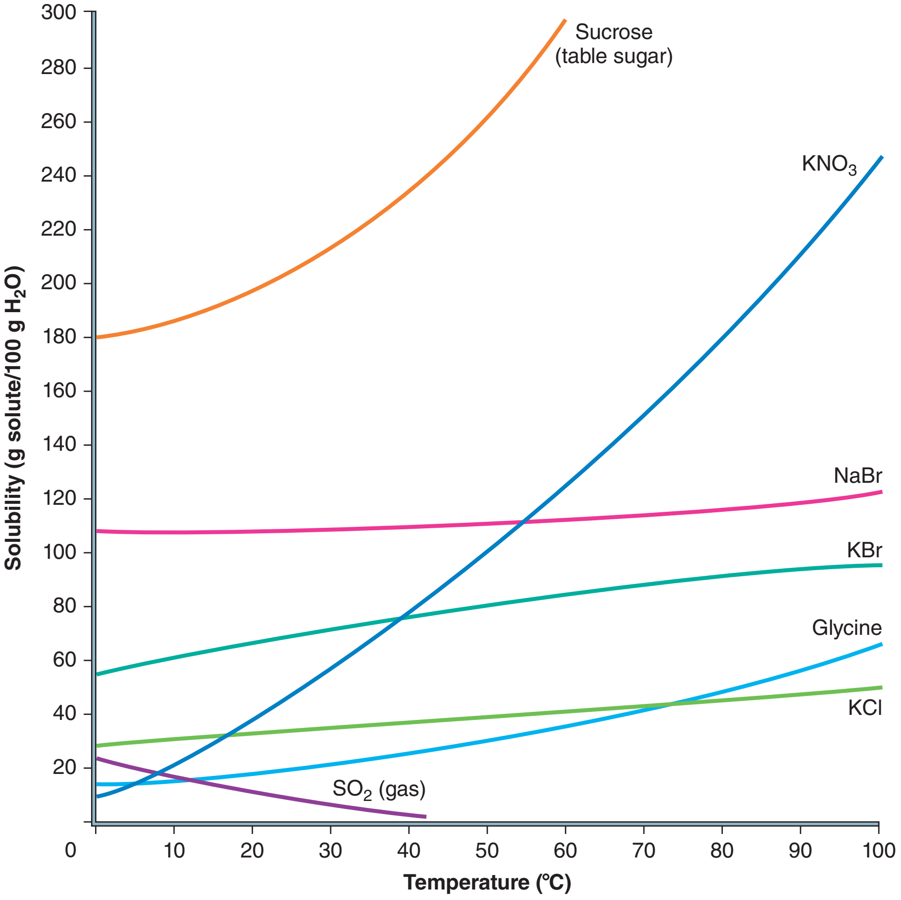


FIGURE 7.4 The effect of temperature on solute solubility.

Whereas the solubility of most liquids and solids in water increases with temperature, the solubility of most gases in water decreases as the temperature increases (see the SO_2 curve in **Figure 7.4**). This is easily demonstrated for gaseous CO_2 by opening both a cold and a warm carbonated beverage. The solubility of gaseous solutes is also influenced significantly by pressure; the effect on liquid or solid solutes is minimal. It has been found that the solubility of many gases is directly proportional to the pressure of the gas above the solution at constant temperature. Thus, if the gas pressure is doubled, the solubility doubles.

The pressure dependence of gas solubility provides the "sparkle" for carbonated beverages. The cold beverage is saturated with CO_2 and capped under pressure. When the bottle is opened, the pressure is relieved, and the gas, now less soluble, comes out of solution as fine bubbles (see **Figure 7.5**). A similar effect sometimes takes place in the bloodstream of deep-sea divers. While submerged, they inhale air under pressure that causes nitrogen to be more soluble in the blood than it is under normal atmospheric pressure. If the diver is brought to the lower pressure on the surface too quickly, the excess dissolved nitrogen comes out of solution and forms bubbles in the blood and joints. The result, called decompression sickness or the bends, is painful and dangerous. The chances of getting the bends are decreased by breathing a mixture of oxygen and helium rather than air (oxygen and nitrogen), because helium is less soluble in the body fluids than nitrogen.

Image Source/Getty Images

FIGURE 7.5 As the pressure is released on a carbonated beverage, the solubility of CO_2 decreases, allowing gaseous bubbles of CO_2 to rise to the surface.

Example 7.2 Temperature and Solute Solubilities

A 260 g sample of table sugar is added to 100 g of water at 70°C. The sugar dissolves completely. The resulting solution is allowed to cool slowly at 30°C. Crystals of sugar begin to form and increase in size as the solution cools to 20°C. Refer to **Figure 7.4** and describe the nature of the solution at 70°, 60°, 50°, 40°, 30°, and 20°C.

Solution

The solubility of sugar is greater than 260 g/100 g H_2O at all temperatures above 50°C. Therefore, the solution is unsaturated at 70°C and 60°C. At 50°C, the solubility is equal to the amount dissolved, so the solution is saturated. At 40°C, the solution contains more dissolved sugar than it should on the basis of solubility, and the solution is supersaturated. At 30°C, the excess sugar crystallizes from solution, and the resulting solution becomes saturated. From that point, excess sugar continues to crystallize from the solution, and the solution remains saturated to 20°C.

✔ **LEARNING CHECK 7.2** Refer to **Figure 7.4**. Saturated solutions of potassium nitrate (KNO_3) and sodium bromide (NaBr) are made at 80°C. Which solution contains more solute per 100 g of H_2O? The solutions are cooled to 50°C, and excess solute crystallizes out of each solution. Which solution at 50°C contains more solute per 100 g of H_2O? Are the solutions saturated at 50°C?

7.3 The Solution Process

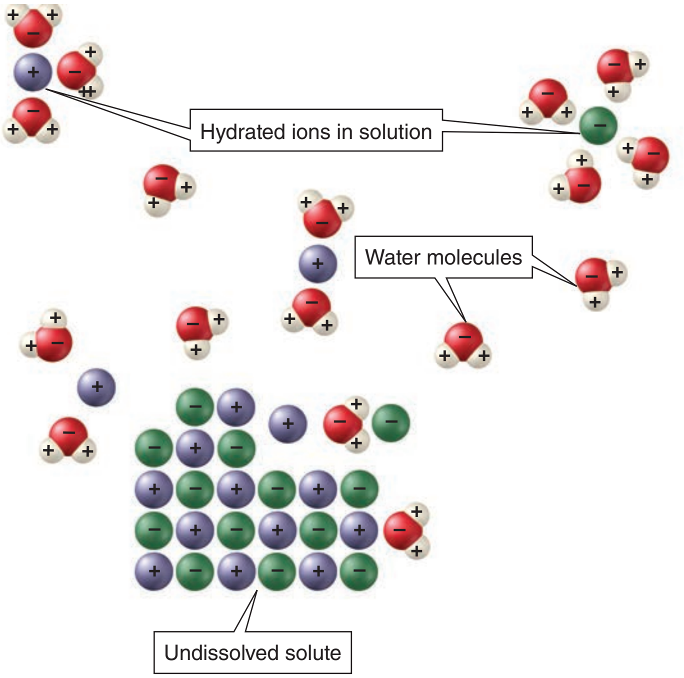
Learning Objective 3 Predict in a general way the solubilities of solutes in solvents on the basis of molecular polarity.

The how and why of solution formation are the topics of this section. How are solute particles removed from the bulk solute and uniformly distributed throughout the solvent? Why are some solutes very soluble whereas others are not?

Consider the formation of a saltwater solution. Earlier we pointed out (see **Section 4.2**) that solid ionic compounds are collections of ions held together by attractions between the opposite ionic charges. When an ionic compound dissolves, the orderly ionic arrangement is destroyed as the interionic attractions are overcome. Thus, the attractive forces between water molecules and ions must be stronger than the interionic attractions within the crystal.

The solution-forming process for an ionic solute is represented in **Figure 7.6**. When the solid ionic crystal is placed in water, the polar water molecules become oriented so that the negative oxygen portion points toward positive sodium ions, and the positive hydrogen portion points toward negative chloride ions. As the polar water molecules begin to surround ions on the crystal surface, they tend to create a shielding effect that reduces the attraction

FIGURE 7.6 The dissolving of an ionic substance in water.



between the ion and the remainder of the crystal. As a result, the ion breaks away from the crystal surface and is surrounded by water molecules. Ions surrounded by water molecules in solution are called **hydrated ions**. As each ion leaves the surface, others are exposed to the water, and the crystal is picked apart ion by ion. Once in solution, the hydrated ions are uniformly distributed by stirring or by random collisions with other molecules or ions.

hydrated ions Ions in solution that are surrounded by water molecules.

The random motion of solute ions in solution causes them to collide with one another, with solvent molecules, and occasionally with the surface of any undissolved solute. Ions undergoing such collisions occasionally stick to the solid surface and thus leave the solution. When the number of ions in solution is low, the chances for collision with the undissolved solute are low. However, as the number of ions in solution increases, so do the chances for such collisions, and more ions leave the solution and become attached once again to the solid. Eventually, the number of ions in solution reaches a level at which ions return to the undissolved solute at the same rate as other ions leave. At this point the solution is saturated, an equilibrium condition. Even though the processes of leaving and returning continue, no net changes in the number of ions in solution or the amount of undissolved solute can be detected as time passes, and an experimenter would observe that no more solid solute dissolves.

Supersaturated solutions form when there are no sites with which the excess solute particles can collide. The addition of such sites in the form of a seed crystal of solute causes the excess solute to crystallize from solution very quickly.

Polar but non-ionic solutes such as sugar dissolve in water in much the same way as ionic solutes. The only difference is the attraction of polar water molecules to both poles of the solute molecules. The process is represented in **Figure 7.7**.

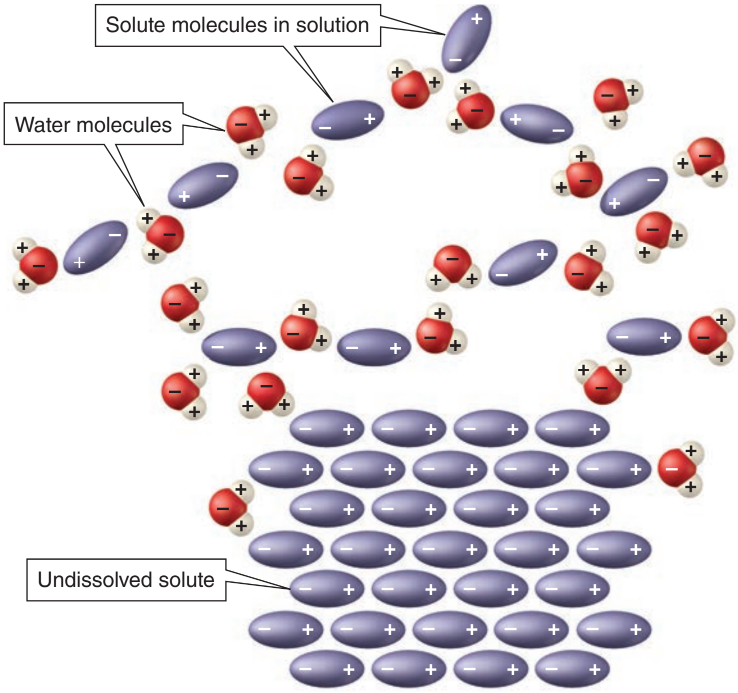


FIGURE 7.7 The dissolving of a polar solute in water.

This solution-forming process also explains the low solubility of some solutes. A solute will not dissolve in a solvent if (1) the forces between solute particles are too strong to be overcome by interactions with solvent particles or (2) the solvent particles are more strongly attracted to each other than to solute particles.

The cooking oil of the earlier experiment did not dissolve in water because the polar water molecules were attracted to each other more strongly than they were to the nonpolar oil molecules (see **Figure 7.8**). The cooking oil will dissolve in a nonpolar solvent such as gasoline or carbon tetrachloride (CCl_4). In these solvents, the weak forces between oil molecules and solvent molecules are no stronger than the weak forces between nonpolar solvent molecules. A good rule of thumb is "like dissolves like." Thus, polar solvents will dissolve polar or ionic solutes, and nonpolar solvents will dissolve nonpolar or non-ionic solutes.

AP Images/Mark Thiessen

FIGURE 7.8 Wildlife can be severely impacted by oil spills because of the insolubility of oil in water. Since most oils float, the creatures most affected are sea otters and seabirds.

These generalizations apply best to non-ionic compounds. Some ionic compounds (such as $CaCO_3$ and $CaSO_4$) have very low solubilities in water (see **Table 7.2**). Both the attractive forces between ions and the attraction of polar solvent molecules for ions are electrical and depend on such characteristics as ionic charge and size. Changes in ionic compounds that increase the attractive forces between ions also increase the forces between ions and polar solvent molecules, but not always by the same amount. Thus, simple rules for quantitatively predicting the water solubility of ionic compounds are not available. (We can't easily predict how many grams will dissolve in a specific quantity of water.) However, ionic compounds are generally insoluble in nonpolar solvents; they usually follow the solubility guidelines given in **Table 7.4** when water is the solvent.

TABLE 7.4 General Solubilities of Ionic Compounds in Water

Compounds	Solubility	Exceptions
Group IA (Na^+, K^-, etc.) and NH_4^+	Soluble	
Nitrates (NO_3^-)	Soluble	
Acetates ($C_2H_3O_2^-$)	Soluble	
Chlorides (Cl^-)	Soluble	Chlorides of Ag^+, Pb^{2+}, Hg^+ (Hg_2^{2+})
Sulfates (SO_4^{2-})	Soluble	Sulfates of Ba^{2+}, Sr^{2+}, Pb^{2+}, Hg^+ (Hg_2^{2+})
Carbonates (CO_3^{2-})	Insoluble[a]	Carbonates of group IA and NH_4^+
Phosphates (PO_4^{3-})	Insoluble[a]	Phosphates of group IA and NH_4^+

[a] Many hydrogen carbonates (HCO_3^-) and phosphates (HPO_4^{2-}, $H_2PO_4^-$) are soluble.

Example 7.3 Predicting Solute Solubilities

The solubility of drugs is a critical factor, so that they can be transported in the aqueous pathways of the body.

Predict the solubility of the following solutes in the solvent indicated:

a. ammonia gas (NH_3) in water
b. oxygen gas (O_2) in water
c. $Ca(NO_3)_2$ in water
d. $Mg_3(PO_4)_2$ in water
e. paraffin wax (nonpolar) in CCl_4

Solution

a. Soluble: Both NH_3 and H_2O are polar—like dissolves like. The actual solubility at 20°C is 51.8 g/100 g H_2O.
b. Insoluble: O_2 is nonpolar. The actual solubility at 20°C is 4.3×10^{-3} g/100 g H_2O.
c. Soluble: nitrates are soluble in water (**Table 7.4**).
d. Insoluble: phosphates are insoluble except those of group IA(1) and NH_4^+ (**Table 7.4**).
e. Soluble: Both CCl_4 and paraffin wax are nonpolar—like dissolves like.

✔ LEARNING CHECK 7.3

a. Refer to **Table 7.4** and decide which of the following salts you would use as a solute if you wanted to prepare a solution that contained as many barium ions (Ba^{2+}) as possible: $BaSO_4$, $Ba(NO_3)_2$, or $BaCO_3$. Explain your answer.
b. A common sight on the evening TV news in the late 1960s and 1970s was sea birds soaked with crude oil being cleaned by concerned people. Which of the following do you think was used to clean the oil from the birds—light mineral oil, purified water, seawater, or gasoline? Explain your answer.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Be careful not to confuse solute solubility with the rate at which a solute dissolves. Under some conditions, even a very soluble solute will dissolve slowly—for example, a lump of rock candy (sugar) dissolves much more slowly than an equal weight of granulated sugar. The dissolving rate can be increased in a number of ways (see **Figure 7.9**):

1. *Crushing or grinding the solute*—small particles provide more surface area for solvent attack and dissolve more rapidly than larger particles.
2. *Heating the solvent*—solvent molecules move faster and have more frequent collisions with solute at higher temperatures.
3. *Stirring or agitating the solution*—stirring removes locally saturated solution from the vicinity of the solute and allows unsaturated solvent to take its place.

© Cengage Learning/West

FIGURE 7.9 Heat and agitation increase the rate at which solutes dissolve. Will sugar dissolve faster in hot tea or iced tea?

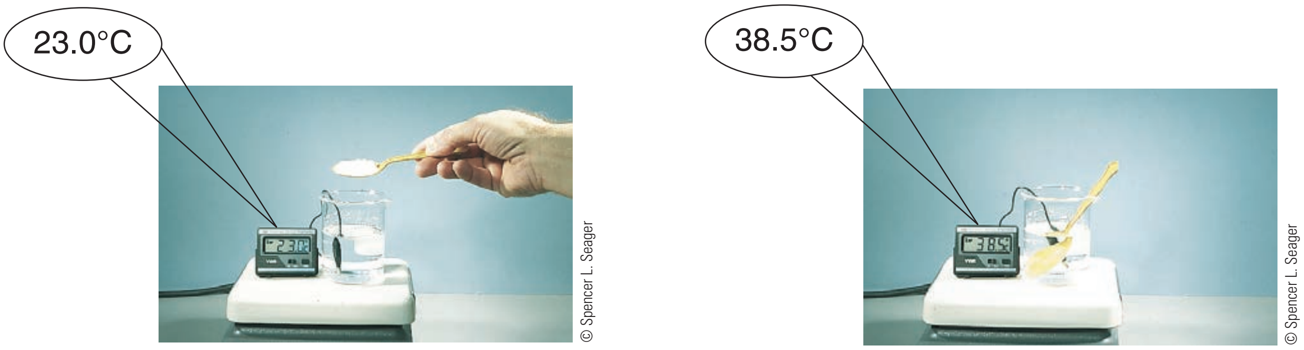
Heat is usually absorbed or released when a solute dissolves in a solvent. When heat is absorbed, the process is endothermic, and the solution becomes cooler. The fact that heat absorption leads to cooling might sound strange, and it needs to be explained. The heat is absorbed by the interacting solvent and solute molecules, and it is removed from the solvent molecules that are not involved in the actual attack on the solute. Since most of the solvent is in the latter category, the entire solution becomes cooled.

When heat is released, the process is exothermic, and the solution temperature increases this time, because the heat released by the interacting molecules is absorbed by the uninvolved solvent. This behavior is the more common one. These processes can be represented by equations:

$$\text{Endothermic:}\quad \text{Solute} + \text{solvent} + \text{heat} \rightarrow \text{solution} \qquad (7.1)$$

$$\text{Exothermic:}\quad \text{Solute} + \text{solvent} \rightarrow \text{solution} + \text{heat} \qquad (7.2)$$

An endothermic solution process is the basis for commercially available instant cold packs. Water is sealed in a thin plastic bag and placed inside a larger, stronger bag together with a quantity of solid solute (NH_4Cl or NH_4NO_3). When the inner bag is broken by squeezing, the solid dissolves in the water, heat is absorbed, and the mixture becomes quite cold (see **Figure 7.10**).

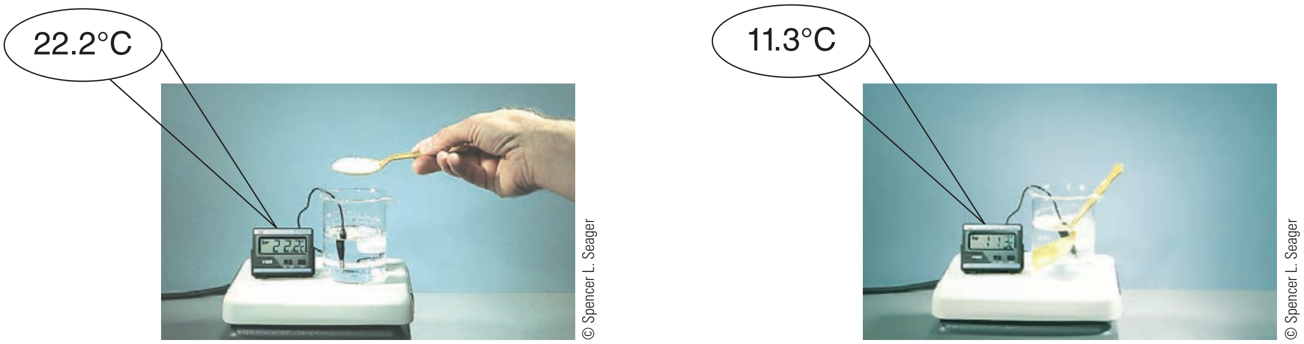


© Spencer L. Seager

© Spencer L. Seager

1 Solid NaOH not yet added to water.

2 Solution becomes hot when NaOH dissolves in water.



© Spencer L. Seager

© Spencer L. Seager

3 Solid NH_4NO_3 not yet added to water.

4 Solution becomes cool when NH_4NO_3 dissolves in water.

FIGURE 7.10 Exothermic (top) and endothermic (bottom) solution processes.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

7.4 Solution Concentrations

Learning Objective 4 Calculate solution concentrations in units of molarity, weight/weight percent, weight/volume percent, and volume/volume percent.

In Chapter 5, quantitative calculations were done using equations for reactions such as the following:

$$CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l) \qquad (7.3)$$

The reaction represented by this equation, and most of the reactions we have discussed up to this point in the book, involve pure substances as reactants and products. However, many of the reactions done in laboratories, and most of those that go on in our bodies, take place between substances dissolved in a solvent to form solutions. In our bodies, the solvent is almost always water. A double-replacement reaction of this type done in laboratories is represented by the following equation:

$$2AgNO_3(aq) + Na_2CO_3(aq) \rightarrow Ag_2CO_3(s) + 2NaNO_3(aq) \qquad (7.4)$$

Hemera Technologies/PhotoObjects.net/Getty Images

FIGURE 7.11 The concentration of every component in an intravenous solution is shown on the label.

concentration The relationship between the amount of solute and the specific amount of solution in which it is contained.

molarity (M) A solution concentration expressed in terms of the number of moles of solute contained in a liter of solution.

We remember from Chapter 5 that the coefficients in equations such as Equation 7.3 allow the relative number of moles of pure reactants and products involved in the reaction to be determined. These relationships coupled with the mole definition in terms of masses then yield factors that can be used to solve stoichiometric problems involving the reactants and products. Similar calculations can be done for reactions that take place between the solutes of solutions if the amount of solute contained in a specific quantity of the reacting solutions is known. Such relationships are known as solution **concentrations** (see **Figure 7.11**). Solution concentrations may be expressed in a variety of units, but only two, molarity and percentage, will be discussed at this time.

The **molarity (M)** of a solution expresses the number of moles of solute contained in exactly 1 L of the solution:

$$M = \frac{\text{moles of solute}}{\text{liters of solution}} \qquad (7.5)$$

It is important to note that even though a concentration in molarity expresses the number of moles contained in 1 L of solution, the molarity of solutions that have total volumes different from 1 L can be calculated using Equation 7.5. We simply determine the number of moles of solute contained in a specified volume of solution, then express that volume in liters before substituting the values into Equation 7.5.

Example 7.4 Calculating Solution Concentrations

Express the concentration of each of the following solutions in terms of molarity:

a. 2.00 L of solution contains 1.50 mol of solute.

b. 315 mL of solution contains 10.3 g of isopropyl alcohol, C_3H_7OH.

Solution a.

STEP 1: Examine the question for what is given and what is unknown.

Given: $V = 2.00$ L
Unknown: M (molarity) = ?
moles = 1.50 mol

STEP 2: Identify a formula that links the given and unknown terms.

$$\text{Equation 7.5: M (molarity)} = \frac{\text{moles of solute}}{\text{liters of solution}}$$

STEP 3: Enter the data into the formula.

$$M = \frac{1.50 \text{ mol solute}}{2.00 \text{ L solution}} = 0.750 \frac{\text{mol solute}}{\text{L solution}}$$

The solution is 0.750 molar, or 0.750 mol/L.

STEP 4 Check to see whether the answer makes sense.
Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

Solution b.

STEP 1: Examine the question for what is given and what is unknown.

$$\text{Given: } V = 315\text{ mL}$$
$$\text{Unknown: M (molarity)} = ?$$
$$\text{mass} = 10.3\text{ g}$$

STEP 2: Identify a formula that links the given and unknown terms.

$$\text{Equation 7.5: M (molarity)} = \frac{\text{moles of solute}}{\text{liters of solution}}$$

Before Equation 7.5 can be used, the number of moles of solute (isopropyl alcohol) must be determined. This is done as follows, where the factor

$$\frac{1\text{ mol alcohol}}{60.1\text{ g alcohol}}$$

comes from the calculated molecular weight of 60.1 u for isopropyl alcohol:

$$(10.3\ \cancel{\text{g alcohol}})\frac{1\text{ mol alcohol}}{60.1\ \cancel{\text{g alcohol}}} = 0.171\text{ mol alcohol}$$

The solution volume expressed in liters is

$$315\ \cancel{\text{mL}} \times \frac{1\ L}{1000\ \cancel{\text{mL}}} = 0.315\text{ L}$$

STEP 3: Enter the data into the formula.

$$\text{M} = \frac{0.171\text{ mol alcohol}}{0.315\text{ L solution}} = 0.543\ \frac{\text{mol alcohol}}{\text{L solution}}$$

The solution is 0.543 molar, or 0.543 M.

STEP 4: Check to see whether the answer makes sense.
Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

✔ **LEARNING CHECK 7.4** Express the concentrations of each of the following solutions in terms of molarity:

a. 2.50 L of solution contains 1.25 mol of solute.
b. 225 mL of solution contains 0.486 mol of solute.
c. 100. mL of solution contains 2.60 g of NaCl solute.

Sometimes a detailed knowledge of the actual stoichiometry of a process involving solutions is not needed, but some information about the solution concentrations would be useful. When this is true, solution concentrations are often expressed as percentages. In general, a concentration in **percent** gives the amount of solute contained in 100 parts of solution. You saw in **Section 1.10**, that it is convenient to use a formula for percentage calculations because we seldom work with exactly 100 units of anything. The general formula used is:

percent A solution concentration that expresses the amount of solute in 100 parts of solution.

$$\% = \frac{\text{part}}{\text{total}} \times 100$$

Three different percent concentrations for solutions are used. A **weight/weight percent** (abbreviated w/w) is the mass of solute contained in 100 mass units of solution. Thus, a 12.0% (w/w) sugar solution contains 12.0 grams of sugar in each 100 g of solution. In terms of this concentration, the general formula for percent calculations becomes

weight/weight percent A concentration that expresses the mass of solute contained in 100 mass units of solution.

$$\%(\text{w/w}) = \frac{\text{solute mass}}{\text{solution mass}} \times 100 \qquad (7.6)$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS 7.1

Stay Hydrated

What should you drink to maintain optimal hydration and health? Many drink products boast that they provide health benefits and energy-boosting power. With all the new "high-tech" beverages available, it can be difficult to make a choice. Fluids lost through metabolism, breathing, sweating, and waste removal are all best replenished by pure water—H_2O. Water quenches your thirst and rehydrates your body. As long as you have access to clean drinking water, plain water beats all other beverages in health benefits. But, how much do you need?

Since everyone's body is different, there is no single recommendation for water consumption that exactly fits everyone. The broadly recommended amount is 125 ounces per day for men and 91 ounces for women. This recommendation includes water consumed by eating food as well as through drinking the liquid. The old-fashioned recommendation of 8 cups a day is about right for most people. Athletes or people living in hot climates will need to drink more than less active people or those living in cooler climates.

Since water is calorie-free and sugar-free, you can't make a healthier choice from the point of view of your body weight and dental health. Water is usually the most affordable beverage choice as well. However, since many cultures promote sugary drinks, choosing plain water can sometimes be difficult. Rather than skip water in favor of a sweet alternative, enhance the flavor of your water with healthy additions such as crushed berries, citrus slices, or fresh mint. These types of additives can be used in combinations to create satisfying flavor-infused water. You can keep a pitcher of flavored water in your refrigerator to use throughout the day.

iStock.com/apomares

Regular fluid intake is a must for participants in vigorous physical activities.

STUDY TOOLS 7.1

Getting Started with Molarity Calculations

Knowing where to start or what to do first is a critical part of working with any math-type problem. First, of course, you must identify a problem as a molarity problem. This can be done by looking for a key word or phrase (molar, molarity, or moles/liter) or the abbreviation M. Second, remember that you have a formula for molarity

$$M = \frac{\text{moles of solute}}{\text{liters of solution}}$$

and the problem might be treated as a formula-type problem. Look for the given numbers and their units, and see if they match the units of the formula. If they do, put them into the formula and do the calculations. For example, if you are asked to calculate the molarity of a solution that contains 0.0856 mol NaCl dissolved in enough water to give 0.100 L of solution, you could put the numbers and their units directly into the formula:

$$M = \frac{0.0856 \text{ mol NaCl}}{0.100 \text{ L solution}} = 0.856 \text{ mol NaCl/L solution}$$

However, if you must calculate the molarity of a solution that contains 5.00 g of NaCl in enough water to give 100. mL of solution, the units of the numbers do not match those of the formula. The factor-unit method can be used to convert each quantity into the units needed by the formula

$$5.00 \cancel{\text{g NaCl}} \times \frac{1 \text{ mol NaCl}}{58.4 \cancel{\text{g NaCl}}} = 0.0856 \text{ mol NaCl}$$

$$100. \cancel{\text{mL solution}} \times \frac{1 \text{ L solution}}{1000. \cancel{\text{mL solution}}} = 0.100 \text{ L solution}$$

These numbers and units can then be put into the formula

$$M = \frac{0.0856 \text{ mol NaCl}}{0.100 \text{ L solution}} = 0.856 \text{ mol NaCl/L solution}$$

Any mass units may be used, but the mass of solute and solution must be expressed in the same units.

A more commonly used percent concentration is **weight/volume percent** (abbreviated w/v), which is the grams of solute contained in 100 mL of solution (see **Figure 7.12**). In these units, a 12.0% (w/v) sugar solution would contain 12.0 g of sugar in each 100 mL of solution. This percent concentration is normally used when the solute is a solid and the solvent and resulting solutions are liquids. The general formula for the calculation of percent concentrations in these units is

$$\%(\text{w/v}) = \frac{\text{grams of solute}}{\text{milliliters of solution}} \times 100 \qquad (7.7)$$

In weight/volume percent calculations, the solute amount is always given in grams, and the solution volume is always given in milliliters.

A percent concentration that is useful when the solute and solvent are either both liquids or both gases is **volume/volume percent** (abbreviated v/v). Concentrations given in these units express the number of volumes of solute found in 100 volumes of solution (see **Figure 7.13**). For these units, the general percentage equation becomes

$$\%(\text{v/v}) = \frac{\text{solute volume}}{\text{solution volume}} \times 100 \qquad (7.8)$$

Any volume units may be used, but they must be the same for both the solute and the solution.

weight/volume percent A concentration that expresses the grams of solute contained in 100 mL of solution.

Jose Luis Pelaez Inc/DigitalVision/Getty Images

FIGURE 7.12 Dextrose 5% (w/v) in water is given intravenously to replace lost fluids and to provide carbohydrates to the body.

volume/volume percent A concentration that expresses the volume of solute contained in 100 volumes of solution.

thodonal/iStock/Getty Images

FIGURE 7.13 Isopropyl rubbing alcohol is generally marketed as 70% alcohol (v/v), which is the concentration that works best as a topical antimicrobial against bacteria, fungi, and viruses.

Example 7.5 More Solution Calculations

The majority of drug concentrations are expressed as a unit of mass per volume or %(w/v).

a. A 150. mL sample of saltwater is evaporated to dryness. A residue of salt weighing 27.9 g is left behind. Calculate the %(w/v) of the original saltwater.

b. A solution is made by mixing 90.0 mL of alcohol with enough water to give 250. mL of solution. What is the %(v/v) concentration of alcohol in the solution?

Solution a.

STEP 1: Examine the question for what is given and what is unknown.

$$\text{Given: grams of solute} = 27.9\text{ g}$$

$$\text{Unknown: }\%\ (\text{w/v}) = ?$$

$$\text{volume of solution} = 150\text{ mL}$$

STEP 2: Identify a formula that links the given and unknown terms.

$$\text{Equation 7.7: }\%(\text{w/v}) = \frac{\text{grams of solute}}{\text{milliliters of solution}} \times 100$$

STEP 3: Enter the data into the formula.

$$\%\ (\text{w/v}) = \frac{27.9\text{ g}}{150.\text{ mL}} \times 100$$

$$= 18.6\ \%\ (\text{w/v})$$

STEP 4: Check to see whether the answer makes sense.

Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

Solution b.

STEP 1: Examine the question for what is given and what is unknown.

$$\text{Given: volume of solute} = 90.0\text{ mL}$$

$$\text{Unknown: }\%(\text{v/v}) = ?$$

$$\text{volume of solution} = 250.\text{ mL}$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STEP 2: Identify a formula that links the given and unknown terms.

$$\text{Equation 7.8: } (\text{v/v}) = \frac{\text{solute volume}}{\text{solution volume}} \times 100$$

STEP 3: Enter the data into the formula.

$$\%\ (\text{v/v}) = \frac{90.0\ \text{mL}}{250.\ \text{mL}} \times 100 = 36.0\%\ (\text{v/v})$$

STEP 4: Check to see whether the answer makes sense.
Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

✔ LEARNING CHECK 7.5

a. A solution is made by dissolving 0.900 g of salt in 100.0 mL of water. Assume that each milliliter of water weighs 1.00 g and that the final solution volume is 100.0 mL. Calculate the %(w/w) and %(w/v) for the solution using the assumptions as necessary.

b. An alcoholic beverage is labeled 90 proof, which means the alcohol concentration is 45% (v/v). How many milliliters of pure alcohol would be present in 1 oz (30.0 mL) of the beverage?

7.5 Solution Preparation

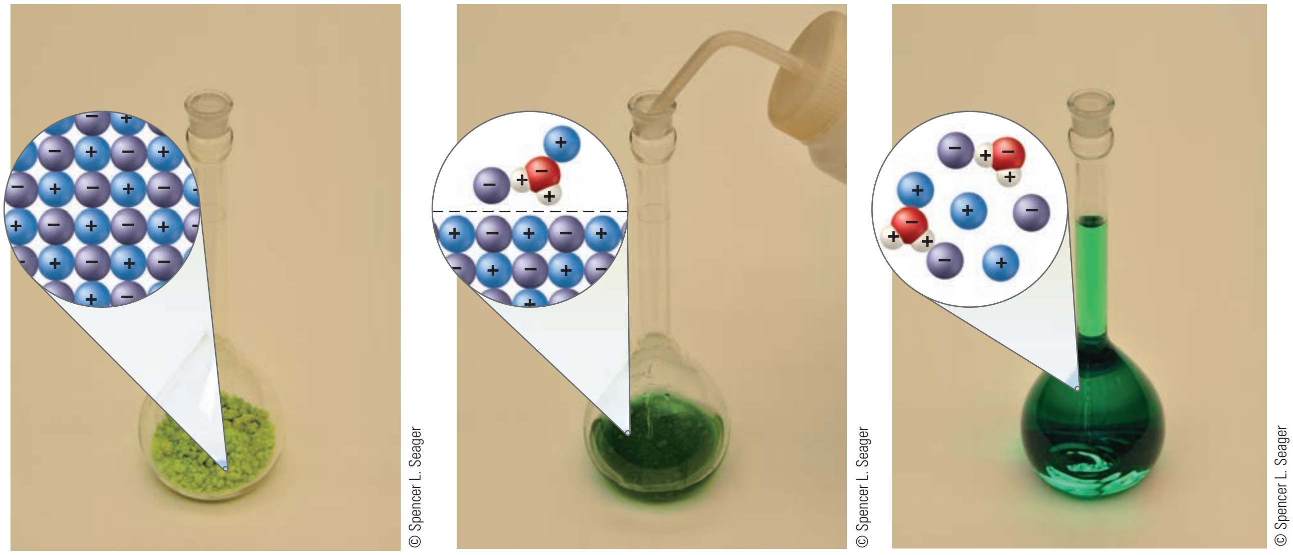
Learning Objective 5 Describe how to prepare solutions of specific concentration using pure solutes and solvent, or solutions of greater concentration than the one desired.

Solutions are usually prepared by mixing together proper amounts of solute and solvent or by diluting a concentrated solution with solvent to produce a solution of lower concentration (see **Figure 7.14**). In the first method, the solute is measured out and placed in a container, and the correct amount of solvent is added. When the concentration is based on solution volume [%(v/v), %(w/v), and M], a volumetric flask or other container is used that, when filled to a specific mark, holds an accurately known volume (see **Figure 7.15**). When the concentration is based on solvent mass [%(w/w)], the correct mass of solvent is added. This mass is usually converted to a volume by using the density, so that a volume of solvent can be measured rather than an amount weighed on a balance.

orange juice

Paul Silverman/Fundamental Photographs

FIGURE 7.14 Orange juice can be prepared by diluting frozen orange juice concentrate with water.



© Spencer L. Seager

© Spencer L. Seager

© Spencer L. Seager

a *Step 1.* Put 0.125 mol of solute into a 250-mL flask.

b *Step 2.* Add some water and dissolve the solute.

c *Step 3.* Fill the flask to the mark with water. Mix thoroughly.

FIGURE 7.15 Preparation of a 0.500 M solution. Use the data given in the figure and show by a calculation that the resulting solution is 0.500 M.

Example 7.6 Preparing Solutions

The ability to prepare solutions is a basic and valuable clinical skill.

Describe how you would prepare the following solutions from pure solute and water:

a. 1.00 L of 1.50 M $CoCl_2$ solution
b. 250. mL of 0.900% (w/v) NaCl solution
c. 500. mL of 8.00% (v/v) methyl alcohol solution

Solution a.

STEP 1: Examine the question for what is given and what is unknown.

Given: volume of 1.00 L
Unknown: moles and grams of $CoCl_2$ needed = ?
concentration of 1.50 M

STEP 2: Identify a formula that links the given and unknown terms.

$$\text{Equation 7.5: M (molarity)} = \frac{\text{moles of solute}}{\text{liters of solution}}$$

This equation can be rearranged to calculate the moles of solute required:

$$(\text{M})(\text{liters of solution}) = \text{moles of solute}$$

STEP 3: Enter the data into the formula.

$$\left(1.50\ \frac{\text{mol}}{\cancel{\text{L}}}\right)(1.00\ \cancel{\text{L}}) = 1.50\ \text{mol}$$

The formula weight of $CoCl_2$ is 129.9 u. The mass of solute is calculated:

$$(1.50\ \cancel{\text{mol CoCl}_2})\left(\frac{129.9\ \text{g CoCl}_2}{1\ \cancel{\text{mol CoCl}_2}}\right) = 195\ \text{g CoCl}_2$$

The solution is prepared by weighing out 195 g $CoCl_2$, putting it into a 1 L volumetric flask, and adding enough water to fill the flask to the mark (see **Figure 7.14**). It is a good practice to let the solute dissolve completely in part of the solvent before filling the flask to the mark.

STEP 4: Check to see whether the answer makes sense.
Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

Solution b.

STEP 1: Examine the question for what is given and what is unknown.

Given: volume of 250. mL
Unknown: weight of solute, w = ?
concentration of 0.900 % (w/v)

STEP 2: Identify a formula that links the given and unknown terms.

$$\text{Equation 7.7: }\%(\text{w/v}) = \frac{\text{grams of solute}}{\text{milliliters of solution}} \times 100$$

This equation can be rearranged to calculate the grams of solute required.

$$\frac{(\%)(\text{milliliters of solution})}{100} = \text{grams of solute}$$

STEP 3: Enter the data into the formula.

$$\frac{(0.900\%)(250.\ \text{mL})}{100} = 2.25\ \text{g NaCl}$$

Thus, the solution is prepared by putting 2.25 g NaCl into a 250-mL volumetric flask and adding water to the mark.

STEP 4: Check to see whether the answer makes sense.
Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Solution c.

STEP 1: Examine the question for what is given and what in unknown.

Given: volume of 500. mL

Unknown: volume of solute, $V = ?$

concentration of 8.00% (v/v)

STEP 2: Identify a formula that links the given and unknown terms.

$$\text{Equation 7.8: } \%(\text{v/v}) = \frac{\text{solute volume}}{\text{solution volume}} \times 100$$

This equation can be rearranged to calculate the volume of solute required.

$$\frac{(\%)(\text{solution volume})}{100} = \text{solute volume}$$

STEP 3: Enter the data into the formula.

$$\frac{(8.00\%)(500.\text{ mL})}{100} = 40.0\text{ mL}$$

Thus, 40.0 mL methyl alcohol is put into a 500 mL volumetric flask, and water is added up to the mark.

STEP 4: Check to see whether the answer makes sense.
Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

✔ **LEARNING CHECK 7.6** Describe how you would prepare the following, using pure solute and water:

a. 0.500 L of 1.00 M $MgCl_2$ solution
b. 0.100 L of 12.0% (w/v) $MgCl_2$ solution
c. 1.00 L of 20.0% (v/v) ethylene glycol solution

Solutions are often prepared by diluting a more concentrated solution with solvent (usually water) to produce a solution of lower concentration. Suppose, for example, that you want to prepare 250. mL of 0.100 M NaCl solution using a 2.00 M NaCl solution as the source of NaCl. First, calculate the number of moles of NaCl that would be contained in 250. mL of 0.100 M solution. Remember Equation 7.5,

$$\text{M} = \frac{\text{moles of solute}}{\text{liters of solution}}$$

which can be rearranged to

$$(\text{M})(\text{liters of solution}) = \text{moles of solute}$$

So, the number of moles of NaCl contained in the desired solution is

$$\left(0.100\ \frac{\text{mol}}{\cancel{\text{L}}}\right)(0.250\ \cancel{\text{L}}) = 0.0250\text{ mol}$$

These moles of NaCl must be obtained from the 2.00 M NaCl solution. The volume of this solution that contains the desired number of moles can be obtained by rearranging Equation 7.5 a different way:

$$\text{liters of solution} = \frac{\text{moles of solute}}{\text{M}}$$

or

$$\text{liters of solution} = \frac{0.0250\ \cancel{\text{mol}}}{2.00\ \cancel{\text{mol}}/\text{L}} = 0.0125\text{ L} = 12.5\text{ mL}$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Thus, the solution is prepared by putting 12.5 mL of 2.00 M NaCl solution into a 250. mL volumetric flask and adding water up to the mark. **Figure 7.16** will help you understand this process.

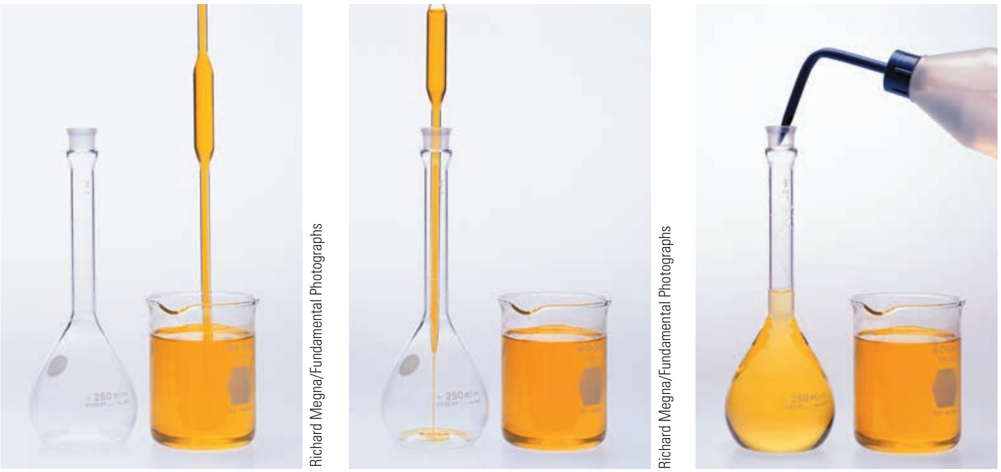


FIGURE 7.16 Preparation of a 0.0400 M $K_2Cr_2O_7$ solution by dilution of a 0.200 M $K_2Cr_2O_7$ solution. Use the data and show by a calculation that the new solution is 0.0400 M.

Richard Megna/Fundamental Photographs

Richard Megna/Fundamental Photographs

Richard Megna/Fundamental Photographs

1 20.0 mL of 0.200 M $K_2Cr_2O_7$ solution is withdrawn from a beaker using a pipette.

2 The 20.0 mL of the 0.200 M $K_2Cr_2O_7$ solution is put into a 100-mL flask.

3 Water is added (while the solution is swirled) to fill the flask to the mark.

The same result can be obtained by using a simplified calculation. Note that the product of concentration in molarity (M) and solution volume in liters will give the number of moles of solute in a sample of solution. In a dilution such as the one done above, the number of moles of solute taken from the concentrated solution and diluted with water is the same as the number of moles of solute in the resulting more dilute solution (see **Figure 7.17**). Thus, the following can be written:

$$\underset{\substack{\text{solute moles in}\\ \text{concentrated solution}}}{M_cV_c} = \underset{\substack{\text{solute moles in}\\ \text{dilute solution}}}{M_dV_d}$$

or

$$(C_c)(V_c) = (C_d)(V_d) \qquad (7.9)$$

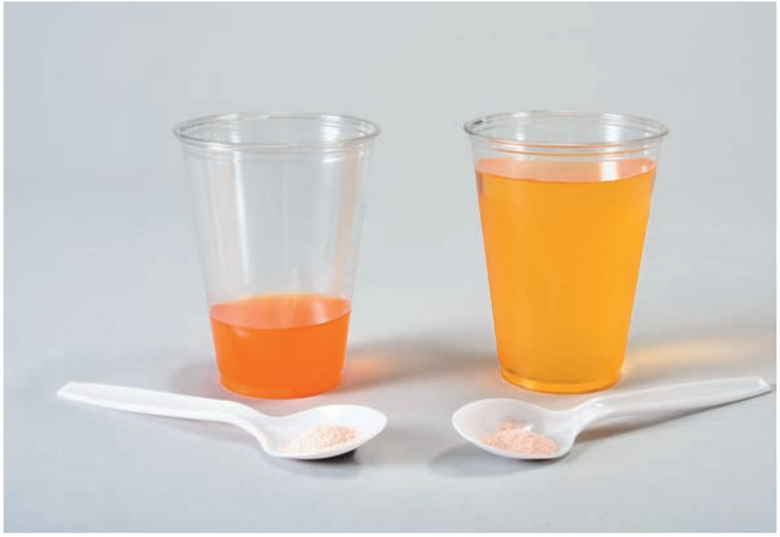


FIGURE 7.17 The concentrated solution (on the left) contains the same amount of solute as the dilute solution (on the right).

Science History Images/Alamy Stock Photo

where the subscripts *c* and *d* refer to the more concentrated and dilute solutions, respectively, and *C* is used to represent any appropriate concentration. An advantage of using this equation is that any volume units may be used, as long as the same one is used for both

V_c and V_d. Also, Equation 7.9 is true for any solution concentration based on volume. This means that M, %(v/v), or %(w/v) concentrations can be used just as long as C_c and C_d are expressed in the same units.

Example 7.7 Preparing Solutions by Dilution

To save preparation time and reduce storage space, some medical solutions are purchased in concentrated form that will be diluted to some lower concentration for actual use.

Use Equation 7.9 and describe how to prepare 250. mL of 0.100 M NaCl solution using a 2.00 M NaCl solution as the source of NaCl.

Solution

STEP 1 Examine the question for what is given and what is unknown.

$$\text{Given: } C_d = 0.100 \text{ M}$$
$$\text{Unknown: } V_c = ?$$
$$V_d = 250. \text{ mL}$$
$$C_c = 2.00 \text{ M}$$

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{Equation 7.9: } (C_c)(V_c) = (C_d)(V_d)$$

STEP 3 Enter the data into the formula.

$$(2.00 \text{ M})(V_c) = (0.100 \text{ M})(250. \text{ mL})$$

or

$$V_c = \frac{(0.100 \cancel{\text{M}})(250. \text{ mL})}{(2.00 \cancel{\text{M}})} = 12.5 \text{ mL}$$

Thus, we quickly find a volume of 2.00 M NaCl needs to be 12.5 mL, the same result found earlier. This volume of solution is put into a 250-mL flask, and water is added to the mark as before.

STEP 4 Check to see whether the answer makes sense.
Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

✔ **LEARNING CHECK 7.7** Use Equation 7.9 and describe how to prepare 500. mL of a 0.250 M NaOH solution from a 6.00 M NaOH solution.

7.6 Solution Stoichiometry

Learning Objective 6 Do stoichiometric calculations based on solution concentrations.

The stoichiometric calculations of solution reactions can be done using the factor-unit method. The sources of the needed factors will be the mole interpretation of the reactions introduced as statement 2 in **Section 5.9**, and the molarities of the solutions involved in the reactions. Each known solution molarity will provide two factors. For example, the following two factors can be obtained based on a 0.400 M HCl solution:

$$\frac{0.400 \text{ mol HCl}}{1 \text{ L HCl soln.}} \quad \text{and} \quad \frac{1 \text{ L HCl soln.}}{0.400 \text{ mol HCl}}$$

Example 7.8 Solution Reaction Calculations

Solutions of NaOH and HCl react according to the following equation:

$$\text{NaOH(aq)} + \text{HCl(aq)} \rightarrow \text{NaCl(aq)} + \text{H}_2\text{O}(\ell)$$

a. What volume of a 0.250 M NaOH solution contains 0.110 mol of NaOH?

b. What volume of a 0.200 M NaOH solution is needed to exactly react with 0.150 mol of HCl?

c. What volume of a 0.185 M NaOH solution is needed to exactly react with 25.0 mL of 0.225 M HCl solution?

Solution

The factor-unit method (see Study Tools 1.1) works well with solution stoichiometry problems.

a. The known quantity is 0.110 mol of NaOH, and the unit of the unknown quantity is a volume that we will express as L NaOH soln.

STEP 1 0.110 mol NaOH

STEP 2 $0.110\text{ mol NaOH} \qquad = \text{L NaOH soln.}$

STEP 3 $0.110\ \cancel{\text{mol NaOH}} \times \dfrac{1\text{ L NaOH soln.}}{0.250\ \cancel{\text{mol NaOH}}} = \text{L NaOH soln.}$

The factor $\dfrac{1\text{ L NaOH soln.}}{0.250\text{ mol NaOH}}$ came from the known molarity of the NaOH solution as described above.

STEP 4 $0.110 \times \dfrac{1\text{ L NaOH soln.}}{0.250} = 0.44\text{ L NaOH soln.} = 0.440\text{ L NaOH soln.}$

The calculator answer of 0.44 was rounded by adding a trailing zero so the answer had three significant figures to match the three significant figures in 0.110 and 0.250. The number 1 is an exact counting number.

STEP 5 Check to see whether the answer makes sense.

Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

b. The known quantity is 0.150 mol HCl, and the unit of the unknown quantity is the volume of NaOH solution, which we will express as L NaOH soln.

STEP 1 0.150 mol HCl

STEP 2 $0.150\text{ mol HCl} \qquad = \text{L NaOH soln.}$

STEP 3 $0.150\ \cancel{\text{mol HCl}} \times \dfrac{1\ \cancel{\text{mol NaOH}}}{1\ \cancel{\text{mol HCl}}} \times \dfrac{1\text{ L NaOH soln.}}{0.200\ \cancel{\text{mol NaOH}}} = \text{L NaOH soln.}$

Note that two factors were needed to cancel the unit of the known quantity and generate the unit of the unknown quantity. The first factor came from statement 2 for the reaction:

$$\text{NaOH(aq)} + \text{HCl(aq)} \longrightarrow \text{NaCl(aq)} + H_2O(\ell)$$

Statement 2: $1\text{ mol NaOH} + 1\text{ mol HCl} \rightarrow 1\text{ mol NaCl} + 1\text{ mol } H_2O$

The second factor came from the 0.200 M concentration of the NaOH solution. Two factors were possible: $\dfrac{0.200\text{ mol NaOH}}{1\text{ L NaOH soln.}}$ and $\dfrac{1\text{ L NaOH soln.}}{0.200\text{ mol NaOH}}$. The second factor was used because it canceled the *mol NaOH* unit and generated the *L NaOH soln.* unit.

STEP 4 $0.150 \times \dfrac{1}{1} \times \dfrac{1\text{ L NaOH soln.}}{0.200} = 0.75\text{ L NaOH soln.} = 0.750\text{ L NaOH soln.}$

STEP 5 Check to see whether the answer makes sense.

Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Once again, a zero was added to the calculator answer of 0.75 to give an answer with three significant figures to match the three in 0.150 and 0.200. Both of the 1 numbers are exact counting numbers.

c. The known quantity is 25.0 mL of a 0.225 M HCl soln., and the unit of the unknown is the volume of a 0.185 M NaOH soln., which we will express as mL NaOH soln. to match the mL unit of the known quantity.

STEP 1 25.0 mL HCl soln.

STEP 2 25.0 mL HCl soln. $=$ mL NaOH soln.

STEP 3

$$25.0\ \cancel{\text{mL HCl soln.}} \times \frac{0.225\ \cancel{\text{mol HCl}}}{1000.\ \cancel{\text{mL HCl soln.}}} \times \frac{1\ \cancel{\text{mol NaOH}}}{1\ \cancel{\text{mol HCl}}} \times \frac{1000.\ \text{mL NaOH soln.}}{0.185\ \cancel{\text{mol NaOH}}} = \text{mL NaOH soln.}$$

Note that three factors were needed. The first came from the molarity of the HCl solution with the solution volume expressed as 1000. mL rather than 1 L. The second factor came from statement 2 for the reaction as was done in part b. The third factor came from the molarity of the NaOH solution with the solution volume expressed as 1000. mL rather than 1 L.

STEP 4

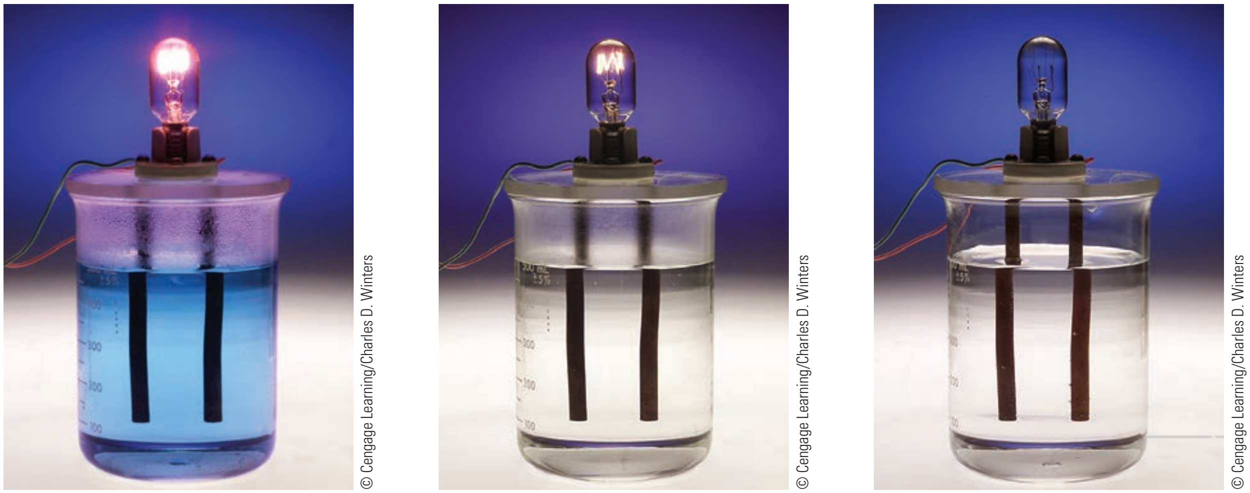
$$25.0 \times \frac{0.225}{1000.} \times \frac{1}{1} \times \frac{1000.\ \text{mL NaOH soln.}}{0.185} = 30.4\ \text{mL NaOH soln.}$$

STEP 5 Check to see whether the answer makes sense.
Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

7.7 Solution Properties

Learning Objective 7 Do calculations based on the colligative solution properties of boiling point, freezing point, and osmotic pressure.

The experiment represented in **Figure 7.18** reveals an interesting property of some solutions. As shown in the figure, the circuit is completed and the light goes on only when the solution conducts electricity. Experiments of this type demonstrate that conductive solutions are formed when soluble ionic materials (see **Section 4.3**), such as sodium chloride, or highly polar covalent materials (see **Section 4.9**), such as hydrogen chloride,


© Cengage Learning/Charles D. Winters

© Cengage Learning/Charles D. Winters

© Cengage Learning/Charles D. Winters

a A solution of a strong electrolyte conducts electricity well.

b A solution of a weak electrolyte conducts electricity poorly.

c A solution of a nonelectrolyte does not conduct electricity.

FIGURE 7.18 Electrical conductivity of solutions.

dissolve in water. Solutes that form conductive water solutions are called **electrolytes**, whereas solutes that form nonconductive solutions are called **nonelectrolytes**. Conductive solutions result when the dissolved solute dissociates, or breaks apart, to form ions, as shown in the following equations representing the dissociation into ions of polar covalent hydrogen chloride and ionic calcium nitrate:

$$HCl(aq) \rightarrow H^{+}(aq) + Cl^{-}(aq) \qquad (7.10)$$

$$Ca(NO_3)_2(aq) \rightarrow Ca^{2+}(aq) + 2NO_3^{-}(aq) \qquad (7.11)$$

Some electrolytes, such as HCl and $Ca(NO_3)_2$, dissociate essentially completely in solution and are called *strong electrolytes*. They form strongly conducting solutions. Other electrolytes, such as acetic acid (the acid found in vinegar), dissociate only slightly and form weakly conductive solutions. These solutes are classified as *weak electrolytes*. The solutes in nonconductive solutions dissolve in the solvent but remain in the form of uncharged molecules.

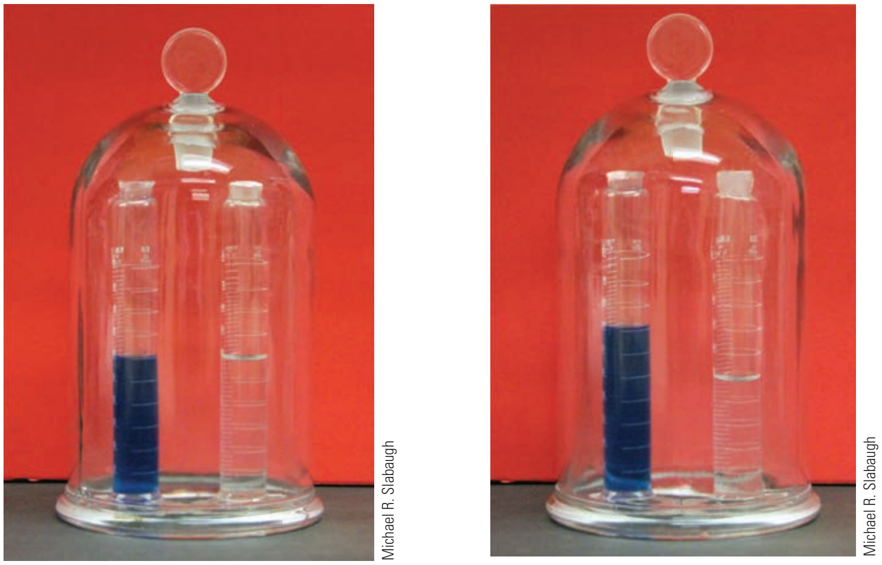
Besides electrical conductivity (or the lack of it), all solutions have properties that depend only on the concentration of solute particles present and not on the actual identity of the solute. Thus, these properties, called **colligative properties**, would be identical for water solutions containing 1 mol of sugar or 1 mol of alcohol per liter.

Three closely related colligative properties are vapor pressure, boiling point, and freezing point. Experiments demonstrate that the vapor pressure of water (solvent) above a solution is lower than the vapor pressure of pure water (see **Figure 7.19**). This behavior causes the boiling point of solutions to be higher than the boiling point of the pure solvent used in the solutions (see **Figure 7.20**), and the freezing point to be lower (see **Table 7.5**).

electrolyte A solute that when dissolved in water forms a solution that conducts electricity.

nonelectrolyte A solute that when dissolved in water forms a solution that does not conduct electricity.

colligative property A solution property that depends only on the concentration of solute particles in solution.


Michael R. Slabaugh

Michael R. Slabaugh

1 Initially, equal volumes of pure water and copper sulfate solution (blue) are placed under a glass dome that prevents water vapor from escaping to the outside.

2 After some time has passed, the volume of pure water has decreased, while that of the copper sulfate solution has increased.

FIGURE 7.19 The vapor pressure of water above a solution is lower than the vapor pressure of pure water. Remember that pressure is a force per unit area. Think of this force as "pushing" water molecules in the vapor state, and explain the process shown in the photos.

TABLE 7.5 A Comparison of Colligative Properties of Pure Solvent and Solutions

Property	Pure Solvent	Solution
Vapor pressure	Normal	Lower than pure solvent
Boiling point	Normal	Higher than pure solvent
Freezing point	Normal	Lower than pure solvent

New Africa/Shutterstock.com

FIGURE 7.20 Using a water–antifreeze mixture gives rise to a higher boiling point and a lower freezing point than pure water.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The boiling and freezing point differences between pure solvent and solutions can be calculated by using an equation of the general form

$$\Delta T = nKm \tag{7.12}$$

In this equation, m is the solution concentration expressed as a molality, a unit we have not discussed. For very dilute solutions, the molality m and molarity M are essentially equal, and M can be used in Equation 7.12 instead of m. This approximation will be used for calculating colligative properties of solutions in this book. The symbol ΔT is the boiling point or freezing point difference between pure solvent and solution. The specific equations used to calculate ΔT for boiling and freezing points are

$$\Delta T_b = nK_b\mathrm{M} \tag{7.13}$$

$$\Delta T_f = nK_f\mathrm{M} \tag{7.14}$$

The subscripts b and f refer to boiling and freezing, respectively, and K_b and K_f are constants characteristic of the solvent used in the solution (remember, to this point we have focused on water as the solvent). Values for K_b and K_f are given in **Table 7.6** for a number of solvents. In Equations 7.13 and 7.14, M is the molarity of solute in solution, and n is the number of moles of solute particles put into solution when 1 mol of solute dissolves.

TABLE 7.6 Boiling and Freezing Point Constants for Various Solvents

Solvent	Normal Boiling Point (°C)	K_b (°C/M)	Normal Freezing Point (°C)	K_f (°C/M)
Benzene	80.1	2.53	5.5	4.90
Camphor			174.0	40.0
Carbon tetrachloride	76.8	5.03		
Chloroform	61.2	3.63		
Cyclohexane	81.0	2.79	6.5	20.0
Ethyl alcohol	78.5	1.22		
Water	100.0	0.52	0.0	1.86

Example 7.9 Solution Boiling and Freezing Points

Freezing point is a critical factor for organisms that try to survive seasonal cold temperatures. Many species of fish, insects, and plants produce substances whose main function is to lower the freezing point of solutions within tissues, protecting those species against freezing temperatures.

Calculate the boiling and freezing points of the following solutions:
171 g of sugar ($C_{12}H_{22}O_{11}$) is dissolved in enough water to give 1.00 L of solution.

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: mass of sugar = 171 g
Unknown: boiling point = ?
volume of solution = 1.00 L
freezing point = ?

STEP 2 Identify a formula that links the given and unknown terms.

Equation 7.13: $\Delta T_b = nK_b\mathrm{M}$

Equation 7.14: $\Delta T_f = nK_f\mathrm{M}$

STEP 3 Enter the data into the formula.

To find the boiling point, calculate solution molarity.

$$(171\ \cancel{g\ C_{12}H_{22}O_{11}})\left(\frac{1\ \text{mol}\ C_{12}H_{22}O_{11}}{342.0\ \cancel{g\ C_{12}H_{22}O_{11}}}\right) = 0.500\ \text{mol}\ C_{12}H_{22}O_{11}$$

$$\text{M} = \frac{\text{moles of solute}}{\text{liters of solution}} = \frac{0.500\ \text{mol}}{1.00\ \text{L}} = 0.500\ \frac{\text{mol}}{\text{L}}$$

Determine n: Because sugar does not dissociate on dissolving, $n = 1$. Therefore,

$$\Delta T_b = nK_b\text{M} = (1)(0.52°\text{C}/\cancel{M})(0.500\ \cancel{M}) = 0.26°\text{C}$$

Because boiling points are higher in solutions, we add ΔT_b to the normal boiling point of water:

$$\text{solution boiling point} = 100.°\text{C} + 0.26°\text{C} = 100.26°\text{C} = 100.3°\text{C}$$

To find the freezing point, calculate ΔT_f:

$$\Delta T_f = nK_f\text{M} = (1)(1.86°\text{C}/\cancel{M})(0.500\ \cancel{M}) = 0.93°\text{C}$$

Because freezing points are lower in solutions, we subtract ΔT_f from the normal freezing point of water:

$$\text{solution freezing point} = 0.0°\text{C} - 0.93°\text{C} = -\ 0.93°\text{C} = -0.9°\text{C}$$

STEP 4 Check to see if whether answer makes sense.
Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

Example 7.9 demonstrates the influence of solute dissociation on colligative properties. Even though the solutions in parts a and b have the same molarity, the NH_4Cl dissociates and produces twice as many solute particles in solution. Hence, it causes twice as much change in the colligative properties.

Osmotic pressure, another important colligative property, can be illustrated by some hypothetical experiments. Consider **Figure 7.21**, where a sugar solution is separated from pure water by a barrier (part (a)). The barrier is removed, but the mixture is not stirred (part (b)). After a day or so, the barrier is replaced, with the results shown in (part (c)). These results are not surprising; the sugar has diffused throughout the mixture uniformly. It would have been very surprising if the process had not taken place.

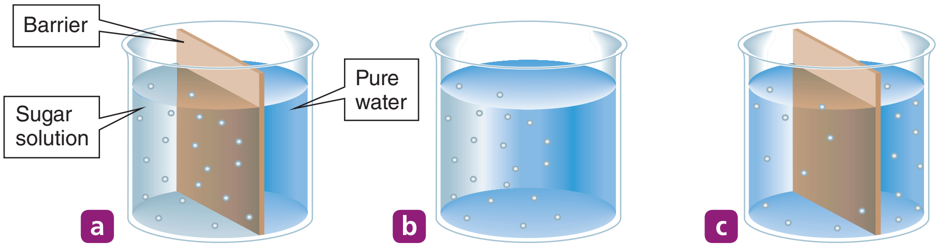
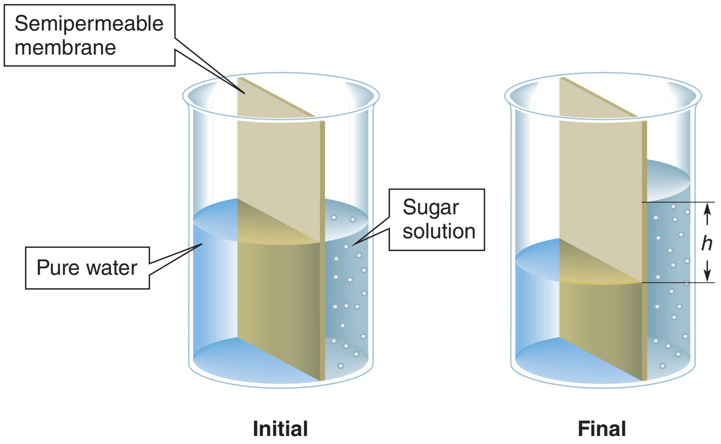


FIGURE 7.21 Diffusion eliminates concentration gradients.

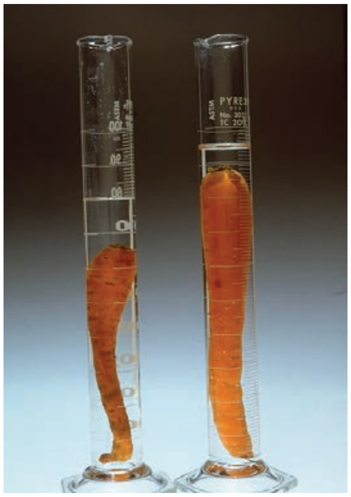
Now consider the experiment shown in **Figure 7.22**, in which two solutions similar to those used before are separated by a semipermeable membrane, which has pores large enough to allow small molecules such as water to pass through but small enough to prevent passage by larger molecules or hydrated ions. In **Figure 7.22**, the membrane allows water molecules to pass but not sugar molecules.

FIGURE 7.22 Osmosis.



osmotic pressure The hydrostatic pressure required to prevent the net flow of solvent through a semipermeable membrane into a solution.

osmosis The process in which solvent molecules flow through a semipermeable membrane into a solution.



© Cengage Learning/Charles D. Winters

FIGURE 7.23 Osmosis through carrot membranes. The tissue of a dried shriveled carrot (left) acts as a semipermeable osmotic membrane when placed in water. After some time, the osmotic flow of water into the carrot rehydrates the carrot (right).

osmolarity The product of n and M in the equation $\pi = nMRT$.

In this experiment, a concentration difference between the liquids has been created, but diffusion is prevented from taking place as it did before. Water molecules move through the membrane in both directions, but sugar molecules cannot move into the pure water to equalize the concentration. As a result, the net flow of water through the membrane is into the sugar solution. This has the effect of increasing the volume of the sugar solution and decreasing its concentration to a value closer to that of the pure water. The movement of water creates a difference in liquid levels (h), which causes hydrostatic pressure against the membrane. This pressure increases until it becomes high enough to balance the tendency for net water to flow through the membrane into the sugar solution. From that time on, the flow of water in both directions through the membrane is equal, and the volume of liquid on each side of the membrane no longer changes. The hydrostatic pressure required to prevent the net flow of water through a semipermeable membrane into a solution is called the **osmotic pressure** of the solution. The process in which solvent molecules move through semipermeable membranes is called **osmosis**. Although our experiment doesn't illustrate it, solvent molecules will also flow osmotically through semipermeable membranes separating solutions of different concentrations. The net flow of solvent is always from the more dilute solution into the more concentrated (see **Figure 7.23**).

The osmotic pressure that will develop across a semipermeable membrane separating pure solvent from a solution of molarity M is given by Equation 7.15, which is similar to the ideal gas law given earlier (see **Section 6.8**):

$$\pi = nMRT \tag{7.15}$$

In this equation, π is the osmotic pressure in units that are the same as the pressure units used in the ideal gas constant R. M is the solution molarity, T is the temperature in kelvins, and n, as before, is the number of moles of solute particles obtained when 1 mol of solute dissolves. Scientists in biological and medical fields often call the product of n and M the **osmolarity** of the solution.

Example 7.10 Osmotic Pressure Calculations

Calculate the osmolarity and the osmotic pressure that would develop across a semipermeable membrane if the solution of Example 7.9 were separated from pure water by the membrane. Assume a solution temperature of 27°C and use an R value of 62.4 L torr/K mol.

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: $T = 27°C$

Unknown: osmolarity = ?

$R = 62.4$ L torr/K mol

Osmotic pressure = ?

M (molarity) = 0.500

STEP 2 Identify a formula that links the given and unknown terms.

$$\text{Osmolarity} = n\text{M}$$

$$\text{Equation 7.1: } \pi \text{ (osmotic pressure)} = n\text{M}RT$$

STEP 3 Enter the data into the formulas.
The molarity of the sugar solution was found to be 0.500 mol/L. Because sugar does not dissociate, n is equal to 1, and the osmolarity nM is also equal to 0.500 mol/L.

$$\pi = n\text{M}RT = (1)\left(0.500\,\frac{\cancel{\text{mol}}}{\cancel{\text{L}}}\right)\left(\frac{62.4\,\cancel{\text{L}}\text{ torr}}{\cancel{\text{K}}\,\cancel{\text{mol}}}\right)(300\,\cancel{\text{K}})$$

$$= 9.36 \times 10^3 \text{ torr}$$

Thus, this solution would develop a pressure sufficient to support a column of mercury 9.36×10^3 mm high. This is equal to about 12.3 standard atmospheres of pressure (see **Table 6.3** for pressure units).

STEP 4 Check to see whether the answer makes sense.
Yes. The answer has the correct unit and the correct number of significant figures, and the value seems reasonable.

✔ **LEARNING CHECK 7.8** Calculate the boiling point, freezing point, and osmotic pressure of the following solutions. Assume that the osmotic pressure is measured at 27°C.

a. A 0.100 M solution of $CaCl_2$ in water. The $CaCl_2$ is a strong electrolyte.
b. A 0.100 M solution of ethylene glycol in water. Ethylene glycol does not dissociate in solution.

7.8 Colloids

Learning Objective 8 Describe the characteristics of colloids.

Like solutions, **colloids** (or colloidal dispersions) are homogeneous mixtures of two or more components in which there is more of one component than of the others. In solutions, the terms *solvent* and *solute* are used for the components, but in colloids, the terms **dispersing medium** (for solvent) and **dispersed phase** (for solute) are used.

Solute particles (in solutions) and dispersed phase particles (in colloids) cannot be seen and do not settle under the influence of gravity. However, solute particles do not scatter or reflect light, whereas dispersed phase particles do. This and other variations in properties result from the principal difference between solutions and colloids, the size of the particles making up the solute or dispersed phase. The dissolved solute in a solution is present in the form of tiny particles (small molecules or ions) that are less than about 10^{-7} cm (0.1 μm) in diameter. The dispersed phase of colloids is made up of much larger particles (very large molecules or small pieces of matter) with diameters of 10^{-7} to 10^{-5} cm (0.1–10 μm). As a result of light scattering, colloids often appear to be cloudy. When a beam of light passes through them, they demonstrate the **Tyndall effect** in which the path of the light becomes visible (see **Figure 7.24**).

The word *colloidal* means "gluelike," and some colloids, including some glues, fit this description quite well. However, many, including smoke, shaving cream, and cheese, do not. Colloids are usually differentiated according to the states of the dispersing medium and dispersed phase. Some colloid types are listed in **Table 7.7**, together with examples and specific names.

Sols that become viscous and semisolid are called *gels.* In these colloids, the solid dispersed phase has a very high affinity for the dispersing medium. The gel "sets" by forming a three-dimensional network of solid and dispersing medium. Other examples of gels are fruit jellies and "canned heat" (jellied alcohol).

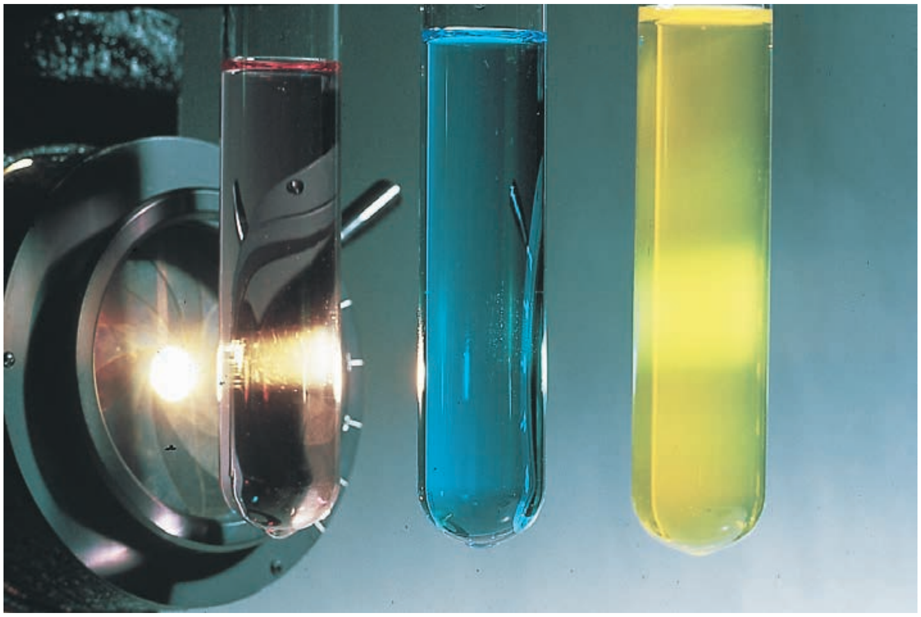
colloid A homogeneous mixture of two or more substances in which the dispersed substances are present as larger particles than are found in solutions.

dispersing medium The substance present in a colloidal dispersion in the largest amount.

dispersed phase The substance present in a colloidal dispersion in amounts less than the amount of the dispersing medium.

Tyndall effect A property of colloids in which the path of a beam of light through the colloid is visible because the light is scattered.

FIGURE 7.24 The Tyndall effect.



© Joel Gordon, courtesy of West Publishing Company/CHEMISTRY by Radel & Navidi, 2d ed

TABLE 7.7 Types of Colloids

Colloid Type			
Dispersing Medium	**Dispersed Phase**	**Name**	**Examples**
Gas	Liquid	Aerosol	Fog, aerosol sprays, some air pollutants
Gas	Solid		Smoke, some air pollutants
Liquid	Gas	Foam	Whipped cream, shaving cream
Liquid	Liquid	Emulsion	Milk, mayonnaise
Liquid	Solid	Sol	Paint, ink, gelatin dessert
Solid	Gas	Solid foam	Marshmallow, pumice stone, foam rubber
Solid	Liquid		Butter, cheese
Solid	Solid		Pearls, opals, colored glass, some metal alloys

Much of the interest in colloids is related to their formation or destruction. Ions that are present in the dispersing medium are attracted to colloid particles and stick on their surfaces. The charge (+ or −) of the ions depends on the nature of the colloid, but all colloid particles within a particular system will attract ions of only one charge or the other. In this way, the colloid particles all acquire the same charge and repel each other. This repulsion helps prevent the particles from coalescing into aggregates large enough to settle out.

In the Cottrel precipitator, colloidal solids are removed from gaseous smokestack wastes before they are released into the atmosphere. The precipitator contains a number of highly charged plates or electrodes. As smoke passes over the charged surfaces, the colloid particles lose their charges. The particles then coalesce into larger particles that settle out and are collected for disposal.

Some colloids are stabilized (prevented from coalescing) by substances known as **emulsifying agents** or **stabilizing agents**. Mayonnaise-like salad dressing is a colloid of oil in water, with compounds from egg yolk acting as the emulsifying agent. These compounds form a coating around the oil droplets, which keeps them separated and suspended in the water.

emulsifying agent (stabilizing agent) A substance that when added to colloids prevents them from coalescing and settling.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS 7.2

Juices and Sports Drinks

Many people believe that fruit juice or sparkling juice is a healthy alternative to soda. This is a mistake, because juices have as many calories and as much sugar as soda, and they are just as detrimental to your dental health and overall body weight. Unlike soda, juice does contribute some vitamins and other nutrients, especially vitamin C. Therefore, adding just a splash of juice to plain water or sparkling water can make the water more palatable and encourage water consumption.

The consumption of high-sugar drinks can cause health problems such as weight gain, increased risk of type 2 diabetes, cardiovascular disease, and gout. The average can of fruit punch or soda contains about 150 calories. Consuming one can of soda per day over the course of a year contributes a weight gain of 5 pounds for the average person. Conversely, eliminating 150 calories per day (or one can of soda) could result in a 5 pound weight reduction (not to mention the reduction in your chances of developing diabetes).

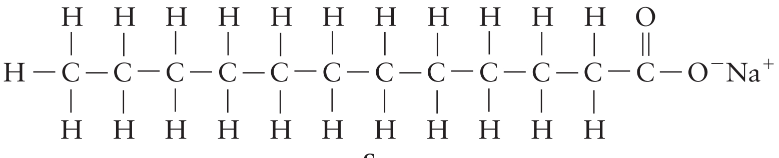
Sports drinks are closely related to soda. They contain a similar number of calories and are designed to deliver carbohydrates and electrolytes to athletes during high-intensity physical workouts. If you are not an athlete burning calories and losing fluid rapidly, sports drinks may not be for you.

Another popular choice is energy drinks. These drinks contain large amounts of sugar and enough caffeine to influence your blood pressure. They also contain additives that produce unknown health effects. If you need a pick-me-up, plain coffee or tea is a better choice. Diet drinks, fruit juice, and milk should also be limited or consumed in moderation. Alcoholic drinks should be limited to no more than one drink per day for women and no more than two drinks per day for men ("one drink" equals 5 oz of wine, one beer, or 1 oz of hard liquor). Clean, refreshing, plain water is always the healthiest choice.

mimagephotography/Shutterstock.com

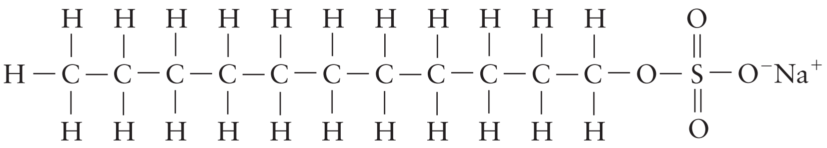
Plain water is always a healthy choice.

The cleaning action of soaps and detergents comes from their activity as emulsifying agents. Both soaps and detergents contain long molecules with structures like the following:



$$\mathrm{H-(CH_2)_{11}-\overset{\overset{\displaystyle O}{\|}}{C}-O^-Na^+}$$

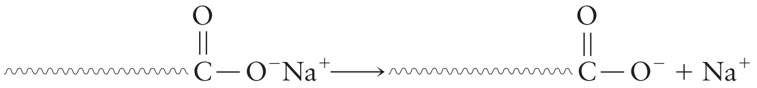
Soap



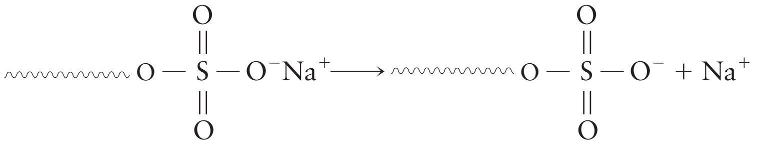
$$\mathrm{H-(CH_2)_{11}-O-\underset{\underset{\displaystyle O}{\|}}{\overset{\overset{\displaystyle O}{\|}}{S}}-O^-Na^+}$$

Detergent

When placed in water, soaps and detergents dissociate to form ions, as shown in Equations 7.16 and 7.17, where the long carbon chains are represented by a wavy line.



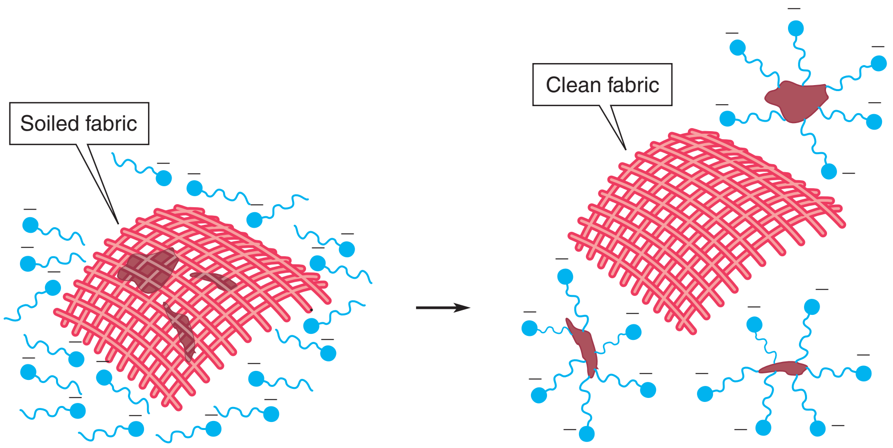
$$\sim\sim\sim\overset{\overset{\displaystyle O}{\|}}{\mathrm{C}}-\mathrm{O^-Na^+}\longrightarrow\sim\sim\sim\overset{\overset{\displaystyle O}{\|}}{\mathrm{C}}-\mathrm{O^-}+\mathrm{Na^+} \qquad (7.16)$$



$$\sim\sim\sim O-\underset{\underset{O}{\|}}{\overset{\overset{O}{\|}}{S}}-O^-Na^+ \longrightarrow \sim\sim\sim O-\underset{\underset{O}{\|}}{\overset{\overset{O}{\|}}{S}}-O^- + Na^+ \quad (7.17)$$

Nonpolar oils and greases are not soluble in water, but they are attracted to the uncharged ends of the soap or detergent ions. As a result of this attraction, the soap or detergent forms a charged layer around the oil droplets, which keeps them separated and suspended (see **Figure 7.25**). Certain compounds (lecithins) of egg yolk act in much the same way to stabilize the mayonnaise-like dressing discussed earlier.

FIGURE 7.25 The cleaning action of soaps and detergents.



Soap ions dissolved in water

Soil particles suspended in water

7.9 Dialysis

dialyzing membrane A semipermeable membrane with pores large enough to allow solvent molecules, other small molecules, and hydrated ions to pass through.

dialysis A process in which solvent molecules, other small molecules, and hydrated ions pass from a solution through a membrane.

Learning Objective 9 Describe the process of dialysis, and compare it to the process of osmosis.

Earlier we discussed semipermeable membranes that selectively allow solvent to pass but retain dissolved solutes during osmosis. **Dialyzing membranes** are semipermeable membranes with larger pores than osmotic membranes. They hold back colloid particles and large molecules but allow solvent, hydrated ions, and small molecules to pass through. The passage of these ions and small molecules through such membranes is called **dialysis**. Dialysis can be used to separate small particles from colloids, as shown in **Figure 7.26**.

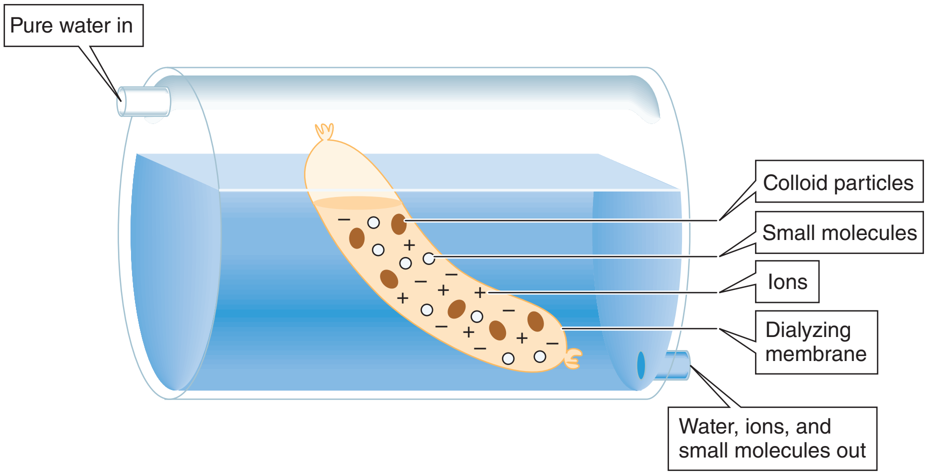


FIGURE 7.26 Dialysis. This is one method of dialysis used to purify proteins.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

ENVIRONMENTAL CONNECTIONS 7.1

CO_2 Emissions: A Blanket Around the Earth

In the same way that a greenhouse heats up when radiant heat energy from the sun is trapped as sunlight passes through its glass or plastic windows, the surface of the Earth warms when radiant solar energy passes through the atmosphere and is trapped. Scientists call this heating of the Earth the "greenhouse effect." Most climate scientists agree that one main cause of current observed climate change is *human activity* that enhances this "greenhouse effect." Since the Industrial Revolution, human activity has influenced the climate.

Certain gases, particularly carbon dioxide (CO_2), water vapor (H_2O), methane (CH_4), and nitrous oxide (N_2O) are called "greenhouse gases" because they act like the windows of a greenhouse and let visible light in but prevent heat from radiating back out. As a result of this effect and the presence of these gases in the Earth's atmosphere, the average temperature at the surface of the Earth is a life-supporting 59°F or 15°C. In naturally occurring amounts these gases make life possible on the Earth, but too much of a good thing can create problems.

The consequences of changing the natural atmospheric concentration of greenhouse gases are difficult to predict and controversial, but one thing is certain. During the past century, based on actual measurements, the average surface temperature of the Earth has increased by up to 0.8°C. Although that might not sound like much, a tiny increase in temperature can have enormous consequences. Glaciers, sea ice, and ice sheets around the world are observed to be melting. As the ice melts, sea levels rise. Also, as sea water warms, it expands and sea levels rise even more. Only humans can change the amount of greenhouse gases produced by human activity, and minimize these negative environmental effects.

iStock.com/Nancy Nehring

An increase in the rate of breakup of glaciers (calving) as they approach the oceans is one indication of global warming.

A mixture containing water, ions, small molecules, and colloid particles is placed inside a bag made from a dialyzing membrane. Water flowing around the bag carries away ions and small molecules that pass through the membrane. Water molecules move through the membrane in both directions, but the colloid particles remain inside the bag.

A similar technique is used to clean the blood of people suffering from kidney malfunction. The blood is pumped through tubing made of a dialyzing membrane. The tubing passes through a bath in which impurities collect after passing out of the blood. Blood proteins and other important large molecules remain in the blood.

Health Career Description

PERSONAL CARE PRODUCT DEVELOPER

A wide variety of positions fall under the title of "personal care product developer," including cosmetic chemists, nutritional supplement chemists, and product developers. In many cases, these careers are accessed through internships held while the intern is working toward a higher degree in chemistry. Similar to an apprenticeship, interns work under established product developers to test and develop new products. Typically, product developers work as part of a larger design team; therefore, small-group communication skills and social skills, as well as knowledge of chemistry and mathematics, are important.

Product developers must make fine distinctions between colors, textures, odors, and other characteristics, so physical sensitivity is required. Computer skills and written communication skills are important in maintaining documentation of product records and in communicating with the design team.

A large nutritional supplement and personal care product company in Ogden, Utah, lists the following job requirements for an assistant product developer:

- Progress toward a bachelor's degree (B.S.) in a scientific or technical field from four-year college or university.

- Must have knowledge of a variety of computer software applications including Microsoft Word and Excel.
- Ability to effectively communicate verbally and in writing.
- Ability to work with mathematical concepts such fractions, percentages, ratios, and proportions and to apply them to practical situations.
- Ability to solve practical problems and deal with a variety of concrete variables in situations where only limited standardization exists. Ability to interpret a variety of instructions furnished in written, oral, diagram, or schedule form.

The posting further states that the applicant works "under limited supervision, conducts product testing and assists in the development of new products."

Personal care product developers may work in the field of cosmetics, foods, nutritional supplements, or hygiene products. Because people consume or apply these products to their bodies, knowledge of toxicity and nutrition is important. Personal care products are part of an extensive and growing industry. Demand for environmentally sensitive, sustainable, quality personal care products is expected to grow.

Source: Nutraceutical Laboratories, Retrieved from: https://recruiting2.ultipro.com/NUT1002NUTRC/JobBoard/e686a42b-cd18-4509-8047-8b5a75be06fe/OpportunityDetail?opportunityId=11a1715f-47f2-43fd-ad30-b275659d46af

Concept Summary

7.1 Physical States of Solutions

Learning Objective: Can you classify mixtures as solutions or nonsolutions based on their appearance?

- Solutions are defined as homogeneous mixtures of a solvent and one or more solutes.
- They can be found in any of the three states of matter: solid, liquid, or gas.
- The physical state of the solution is often the same as the physical state of the solvent.

7.2 Solubility

Learning Objective: Can you demonstrate your understanding of terms related to the solubility of solutes in solution?

- The amount of solute that will dissolve in a quantity of solvent to form a saturated solution is the solubility of the solute.
- Solubility depends on similarities in polarities of the solvent and solute.
- It generally increases with temperature for solid and liquid solutes, but decreases with temperature for gaseous solutes.

7.3 The Solution Process

Learning Objective: Can you predict in a general way the solubilities of solutes in solvents on the basis of molecular polarity?

- The solution process of solid solute in a liquid solvent can be thought of in terms of the solvent molecules attracting the solute particles away from the solute crystal lattice.
- The solute is picked apart and solute particles hydrated as a result of attractions between water molecules and solute particles.
- Heat is generally absorbed or released when a solute dissolves in a solvent.
- When heat is released, the solution process is called exothermic, and the solution temperature increases.
- When heat is absorbed, the solution process is endothermic, and the solution cools as solute dissolves.

7.4 Solution Concentrations

Learning Objective: Can you calculate solution concentrations in units of molarity, weight/weight percent, weight/volume percent, and volume/volume percent?

- Relationships between the amount of solute and the amount of solution containing the solute are called concentrations.
- They may be expressed as molarity, weight/weight percent, weight/volume percent, or volume/volume percent.

7.5 Solution Preparation

Learning Objective: Can you describe how to prepare solutions of specific concentration using pure solutes and solvent, or solutions of greater concentration than the one desired?

- Solutions of specific concentration can be prepared by mixing appropriate amounts of solute and solvent or by diluting a more concentrated solution with solvent.

7.6 Solution Stoichiometry

Learning Objective: Can you do stoichiometric calculations based on solution concentrations?

- When solution concentrations are expressed as molarities, the mole concept can be applied to reactions taking place between substances that are solutes in the solutions.

7.7 Solution Properties

Learning Objective: Can you do calculations based on the colligative solution properties of boiling point, freezing point, and osmotic pressure?

- A number of solution properties differ from the properties of pure solvent.
- Ionic or highly polar solutes that dissociate in solution result in solutions that conduct electricity.
- Colligative solution properties depend on the concentration of solute particles in the solution and include vapor pressure, boiling point, freezing point, and osmotic pressure.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

7.8 Colloids

Learning Objective: Can you describe the characteristics of colloids?

- Homogeneous mixtures called colloids, or colloidal dispersions, differ from solutions in terms of the size of the dispersed phase particles.
- In colloids, the particles are large enough to scatter light and thus show the Tyndall effect.
- Colloids, like solutions, occur in all three physical states, depending primarily on the physical state of the dispersing medium.
- In true colloids, the suspension is permanent because dispersed particles acquire similar charges by the absorbing ions from the dispersing medium and repel each other or because emulsifying agents keep the dispersed particles from coalescing.

7.9 Dialysis

Learning Objective: Can you describe the process of dialysis, and compare it to the process of osmosis?

- Dialyzing membranes are semipermeable but with pores large enough to allow solvent molecules, hydrated ions, and small molecules to pass through in a process called dialysis.
- The process is important in the removal of impurities from the blood and is applied artificially for people suffering from kidney malfunction.

Key Terms and Concepts

Colligative property (7.7)
Colloid (7.8)
Concentration (7.4)
Dialysis (7.9)
Dialyzing membrane (7.9)
Dispersed phase (7.8)
Dispersing medium (7.8)
Dissolving (7.1)
Electrolyte (7.7)
Emulsifying agent (stabilizing agent) (7.8)
Hydrated ions (7.3)
Immiscible (7.2)
Insoluble substance (7.2)
Molarity (M) (7.4)
Nonelectrolyte (7.7)
Osmolarity (7.7)
Osmosis (7.7)
Osmotic pressure (7.7)
Percent (7.4)
Saturated solution (7.2)
Solubility (7.2)
Soluble substance (7.2)
Solute (7.1)
Solution (7.1)
Solvent (7.1)
Supersaturated solution (7.2)
Tyndall effect (7.8)
Volume/volume percent (7.4)
Weight/volume percent (7.4)
Weight/weight percent (7.4)

Key Equations

1. Solution concentration in terms of molarity (**Section 7.4**):	$\text{M} = \dfrac{\text{moles of solute}}{\text{liters of solution}}$	Equation 7.5
2. Solution concentration in terms of weight/weight % (**Section 7.4**):	$\%(\text{w/w}) = \dfrac{\text{solute mass}}{\text{solution mass}} \times 100$	Equation 7.6
3. Solution concentration in terms of weight/volume % (**Section 7.4**):	$\%(\text{w/v}) = \dfrac{\text{grams of solute}}{\text{milliliters of solution}} \times 100$	Equation 7.7
4. Solution concentration in terms of volume/volume % (**Section 7.4**):	$\%(\text{v/v}) = \dfrac{\text{solute volume}}{\text{solution volume}} \times 100$	Equation 7.8
5. Dilution of concentrated solution to make less-concentrated solution (**Section 7.5**):	$(C_c)(V_c) = (C_d)(V_d)$	Equation 7.9
6. Boiling point elevation of a solution (**Section 7.7**):	$\Delta T_b = nK_b\text{M}$	Equation 7.13
7. Freezing point depression of a solution (**Section 7.7**):	$\Delta T_f = nK_f\text{M}$	Equation 7.14
8. Osmotic pressure of a solution (**Section 7.7**):	$\pi = n\text{M}RT$	Equation 7.15

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Physical States of Solutions (Section 7.1)

7.1 Many solutions are found in the home. Some are listed below, with the composition as printed on the label. When no percentage is indicated, components are usually given in order of decreasing amount. When water is present, it is often not mentioned on the label or it is included in the inert ingredients. Identify the solvent and solutes of the following solutions:

- **a.** Antiseptic mouthwash: alcohol 25%, thymol, eucalyptol, methyl salicylate, menthol, benzoic acid, boric acid
- **b.** Paregoric: alcohol 45%, opium 0.4%
- **c.** Baby oil: mineral oil, lanolin (there happens to be no water in this solution—why?)
- **d.** Distilled vinegar: acetic acid 5%

7.2 Many solutions are found in the home. Some are listed below, with the composition as printed on the label. When no percentage is indicated, components are usually given in order of decreasing amount. When water is present, it is often not mentioned on the label or it is included in the inert ingredients. Identify the solvent and solutes of the following solutions:

- **a.** Liquid laundry bleach: sodium hypochlorite 5.25%, inert ingredients 94.75%
- **b.** Rubbing alcohol: isopropyl alcohol 70%
- **c.** Hydrogen peroxide: 3% hydrogen peroxide
- **d.** Aftershave: SD alcohol, water, glycerin, fragrance, menthol, benzophenone-1, coloring

7.3 Classify the following as being a solution or not a solution. Explain your reasons when you classify one as *not* a solution. For the ones classified as solutions, identify the solvent and solute(s).

- **a.** Maple syrup
- **b.** Milk
- **c.** Eyedrops
- **d.** Tomato juice
- **e.** Tap water

7.4 Classify the following as being a solution or not a solution. Explain your reasons when you classify one as *not* a solution. For the ones classified as solutions, identify the solvent and solute(s).

- **a.** Foggy air
- **b.** Tears
- **c.** Freshly squeezed orange juice
- **d.** Strained tea
- **e.** Creamy hand lotion

Solubility (Section 7.2)

7.5 Use the term *soluble, insoluble,* or *immiscible* to describe the behavior of the following pairs of substances when they are shaken together:

- **a.** 25 mL of water and 1 g of salt—the resulting mixture is clear and colorless.
- **b.** 25 mL of water and 1 g of solid silver chloride—the resulting mixture is cloudy and solid settles out.
- **c.** 25 mL of water and 5 mL of mineral oil—the resulting mixture is cloudy and gradually separates into two layers.

7.6 Use the term *soluble, insoluble,* or *immiscible* to describe the behavior of the following pairs of substances when they are shaken together:

- **a.** 25 mL of cooking oil and 25 mL of vinegar—the resulting mixture is cloudy and gradually separates into two layers.
- **b.** 25 mL of water and 10 mL of rubbing alcohol—the resulting mixture is clear and colorless.
- **c.** 25 mL of chloroform and 1 g of roofing tar—the resulting mixture is clear but dark brown in color.

7.7 Rubbing alcohol is used as a topical antiseptic. It is typically a mixture of isopropyl alcohol and water. Because isopropyl alcohol is miscible in water, it can be purchased in a variety of concentrations. Define the term *miscible*. It is *not* defined in the text.

7.8 Classify the following solutions as unsaturated, saturated, or supersaturated:

- **a.** A solution to which a small piece of solute is added, and it dissolves.
- **b.** A solution to which a small piece of solute is added, and much more solute comes out of solution.
- **c.** The final solution resulting from the process in part b.

7.9 Ammonium sulfate is used in pharmacologic preparations to "salt out" unwanted proteins and contaminants. Suppose a technician puts 35.8 g of ammonium sulfate into a flask and adds 100 g of water at 0°C. After stirring to dissolve as much solute as possible, will the technician have a saturated or an unsaturated solution? Explain your answer. Refer to **Table 7.2**.

7.10 Suppose you have a saturated solution that is at room temperature. Discuss how it could be changed into a supersaturated solution without using any additional solute.

7.11 Classify each of the following solutes into the approximate solubility categories of **Table 7.3**. The numbers in parentheses are the grams of solute that will dissolve in 100 g of water at the temperature indicated.

- **a.** boric acid, H_3BO_3 (6.35 g at 30°C)
- **b.** calcium hydroxide, $Ca(OH)_2$ (5.35 g at 30°C)
- **c.** antimony(III) sulfide, Sb_2S_3 (1.75×10^{-4} g at 18°C)
- **d.** copper(II) chloride, $CuCl_2$ (70.6 g at 0°C)
- **e.** iron(II) bromide, $FeBr_2$ (109 g at 10°C)

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

7.12 Classify each of the following solutes into the approximate solubility categories of **Table 7.3**. The numbers in parentheses are the grams of solute that will dissolve in 100 g of water at the temperature indicated.

- **a.** barium nitrate, $Ba(NO_3)_2$ (8.7 g at 20°C)
- **b.** aluminum oxide, Al_2O_3 (9.8×10^{-5} g at 29°C)
- **c.** calcium sulfate, $CaSO_4$ (0.21 g at 30°C)
- **d.** manganese chloride, $MnCl_2$ (72.3 g at 25°C)
- **e.** lead bromide, $PbBr_2$ (0.46 g at 0°C)

The Solution Process (Section 7.3)

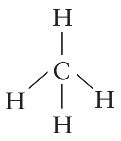
7.13 What is the difference between a nonhydrated ion and a hydrated ion? Draw a sketch using the Cl^- ion to help illustrate your answer.

7.14 Barium sulfate ($BaSO_4$) suspension is often used as a contrast agent to improve visualization of the gastrointestinal tract during CT (computed tomography) scans. Explain why the $BaSO_4$ is in suspension form and not a solution. What do you think a suspension is?

7.15 Ground-up limestone ($CaCO_3$) is used as a gentle abrasive in some powdered cleansers. Why is this a better choice than ground-up soda ash (Na_2CO_3)?

7.16 Indicate which of the following substances (with geometries as given) would be soluble in water (a polar solvent) and in benzene (a nonpolar solvent):

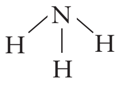
a.



(tetrahedral)

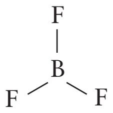
b. Ne

c.



(triangular-based pyramid)

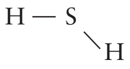
d.



(flat triangle)

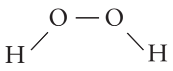
7.17 Indicate which of the following substances (with geometries as given) would be soluble in water (a polar solvent) and in benzene (a nonpolar solvent):

a.



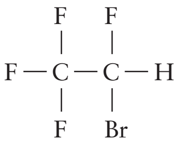
b. HCl

c.



d. $N \equiv N$

7.18 Halothane is a general-use inhalation anesthetic. The molecular structure is:



$$\begin{array}{ccccccc} & & F & & F & & \\ & & | & & | & & \\ F & - & C & - & C & - & H \\ & & | & & | & & \\ & & F & & Br & & \end{array}$$

Explain why halothane would or would not be soluble in water.

7.19 Suppose you put a piece of a solid into a beaker that contains water and stir the mixture briefly. You find that the solid does not immediately dissolve completely. Describe three things you might do to try to get the solid to dissolve.

Solution Concentrations (Section 7.4)

7.20 Calculate the molarity of the following solutions:

- **a.** 1.25 L of solution contains 0.455 mol of solute.
- **b.** 250. mL of solution contains 0.215 mol of solute.
- **c.** 0.175 mol of solute is put into a container and enough distilled water is added to give 100. mL of solution.

7.21 Calculate the molarity of the following solutions:

- **a.** 2.50 L of solution that contains 0.860 mol of solute.
- **b.** 400. mL of solution that contains 0.304 mol of solute.
- **c.** 0.120 mol of solute is put into a container and enough distilled water is added to give 250. mL of solution.

7.22 Calculate the molarity of the following solutions:

- **a.** A sample of solid KBr weighing 11.9 g is put in enough distilled water to give 200.0 mL of solution.
- **b.** A 14.2-g sample of solid Na_2SO_4 is dissolved in enough water to give 500.0 mL of solution.
- **c.** A 10.0-mL sample of solution is evaporated to dryness and leaves 0.29 g of solid residue that is identified as Li_2SO_4.

7.23 Calculate the molarity of the following solutions:

- **a.** A sample of solid Na_2SO_4 weighing 0.140 g is dissolved in enough water to make 10.0 mL of solution.
- **b.** A 4.50-g sample of glucose ($C_6H_{12}O_6$) is dissolved in enough water to give 150. mL of solution.
- **c.** A 43.5-g sample of K_2SO_4 is dissolved in a quantity of water, and the solution is stirred well. A 250.0 mL sample of the resulting solution is evaporated to dryness and leaves behind 2.18 g of solid K_2SO_4.

7.24 Calculate:

- **a.** How many moles of solute is contained in 1.75 L of 0.215 M solution?
- **b.** How many moles of solute is contained in 250. mL of 0.300 M solution?
- **c.** How many milliliters of 0.350 M solution contains 0.200 mol of solute?

7.25 Because concentrations are relatively dilute, intravenous solutions given in hospitals have concentrations listed as mmol/L (millimoles per liter; a millimole is 0.001 of a mole), rather than M (moles per liter). So a 250. mmol/L concentration is the same as 0.250 M. Calculate the following:

- **a.** How many moles of dextrose (blood sugar) are contained in 1.25 L of a 278 mmol/L dextrose solution?
- **b.** How many moles of sodium chloride are contained in 200. mL of a 154 mmol/L saline solution?
- **c.** What volume of a 154 mmol/L saline solution contains 0.500 mol of sodium chloride?

7.26 Calculate:

- **a.** How many grams of solid would be left behind if 20.0 mL of a 0.550 M KCl solution was evaporated to dryness?

b. What volume of a 0.315 M HNO_3 solution is needed to provide 0.0410 mol HNO_3?

c. What volume of 1.21 M NH_4NO_3 contains 50.0 g of solute?

7.27 Calculate:

a. How many grams of solid $AgNO_3$ will be needed to prepare 200. mL of a 0.200 M solution?

b. How many grams of vitamin C ($C_6H_8O_6$) would be contained in 25.0 mL of a 1.00 M solution?

c. How many moles of HCl is contained in 250. mL of a 6.0 M solution?

7.28 Calculate the concentration in %(w/w) of the following solutions. Assume water has a density of 1.00 g/mL.

a. 5.3 g of sugar and 100. mL of water

b. 5.3 g of any solute and 100. mL of water

c. 5.3 g of any solute and 100. g of any solvent

7.29 Calculate the concentration in %(w/w) of the following solutions. Assume water has a density of 1.00 g/mL.

a. 6.5 g of table salt and 100. mL of water

b. 6.5 g of any solute and 100. mL of water

c. 6.5 g of any solute and 100. g of any solvent

7.30 Calculate the concentration in %(w/w) of the following solutions. Assume water has a density of 1.00 g/mL.

a. 20.0 g of salt is dissolved in 250. mL of water.

b. 0.100 mol of solid glucose ($C_6H_{12}O_6$) is dissolved in 100. mL of water.

c. 120. g of solid is dissolved in 100. mL of water.

d. 10.0 mL of ethyl alcohol (density = 0.789 g/mL) is mixed with 10.0 mL of water.

7.31 Calculate the concentration in %(w/w) of the following solutions. Assume water has a density of 1.00 g/mL.

a. 5.20 g of $CaCl_2$ is dissolved in 125 mL of water.

b. 0.200 mol of solid KBr is dissolved in 200. mL of water.

c. 50.0 g of solid is dissolved in 250. mL of water.

d. 10.0 mL of ethyl alcohol (density = 0.789 g/mL) is mixed with 10.0 mL of ethylene glycol (density = 1.11 g/mL).

7.32 Calculate the concentration in %(w/w) of the following solutions:

a. 20.0 g of solute is dissolved in enough water to give 150. mL of solution. The density of the resulting solution is 1.20 g/mL.

b. A 10.0-mL sample with a density of 1.10 g/mL leaves 1.18 g of solid residue when evaporated.

c. A 25.0-g sample of solution on evaporation leaves a 1.87-g residue of $MgCl_2$.

7.33* Calculate the concentration in %(w/w) of the following solutions:

a. 424 g of solute is dissolved in enough water to give 1.00 L of solution. The density of the resulting solution is 1.18 g/mL.

b. A 50.0 mL solution sample with a density of 0.898 g/mL leaves 12.6 g of solid residue when evaporated.

c. A 25.0 g sample of solution on evaporation leaves a 2.32 g residue of NH_4Cl.

7.34 Calculate the concentration in %(v/v) of the following solutions:

a. 200. mL of solution contains 15 mL of alcohol.

b. 200. mL of solution contains 15 mL of any soluble liquid solute.

c. 8.0 fluid ounces of oil is added to 2.0 gallons (256 fluid ounces) of gasoline.

d. A solution of alcohol and water is separated by distillation. A 200.-mL sample gives 85.9 mL of alcohol.

7.35 Calculate the concentration in %(v/v) of the following solutions:

a. 250. mL of solution contains 15.0 mL of acetone.

b. 250. mL of solution contains 15.0 mL of any soluble liquid solute.

c. 1.0 quart of acetic acid is put into a 5-gallon container, and enough water is added to fill the container.

d. A solution of acetone and water is separated by distillation. A 300. mL sample gives 109 mL of acetone.

7.36* Consider the blood volume of an adult to be 5.0 L. A blood alcohol level of 0.50% (v/v) can cause a coma. What volume of pure ethyl alcohol, if consumed in one long drink and assumed to be absorbed completely into the blood, would result in this critical blood alcohol level?

7.37* The blood serum acetone level for a person is determined to be 1.8 mg of acetone per 100. mL of serum. Express this concentration as %(v/v) if liquid acetone has a density of 0.79 g/mL.

7.38 Calculate the concentration in % (w/v) of the following intravenous solutions used in hospitals:

a. 150. mL of a dextrose solution contains 7.50 g of dissolved solid dextrose (glucose).

b. 150. mL of solution contains 7.50 g of any dissolved solid solute.

c. 350. mL of normal saline solution contains 3.15 g of dissolved solid sodium chloride.

7.39 Calculate the concentration in %(w/v) of the following solutions:

a. 26.5 g of solute is dissolved in 200. mL of water to give a solution with a density of 1.10 g/mL.

b. A 30.0-mL solution sample on evaporation leaves a solid residue of 0.38 g.

c. On analysis for total protein, a blood serum sample of 15.0 mL is found to contain 1.15 g of total protein.

7.40 A saturated solution of KBr in water is formed at 20.0ºC. Consult **Figure 7.4** and calculate the concentration of the solution in %(w/w).

7.41 Phenol (C_6H_5OH) is an antiseptic used in some mouthwashes, throat sprays, and lozenges. What is the molarity of phenol in a mouthwash that contains 1.4 g of phenol per 100 mL of solution?

Solution Preparation (Section 7.5)

7.42 Explain how you would prepare the following solutions using pure solute and water. Assume water has a density of 1.00 g/mL.

a. 200. mL of 0.150 M Na_2SO_4 solution

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

b. 250.0 mL of 0.250 M $Zn(NO_3)_2$ solution

c. 150.0 g of 2.25% (w/w) NaCl solution

d. 125.0 mL of 0.75% (w/v) KCl solution

7.43 Explain how you would prepare the following solutions using pure solute and water. Assume water has a density of 1.00 g/mL.

a. 250. mL of a 2.00 M NaOH solution

b. 500. mL of a 40.0% (v/v) alcohol solution (C_2H_5OH)

c. 100. mL of a 15.0% (w/v) glycerol solution. Glycerol is a liquid with a density of 1.26 g/mL. Describe two ways to measure out the amount of glycerol needed.

d. Approximately 50. mL of a normal saline solution, 0.89% (w/w) NaCl

7.44* A saline solution used for intravenous injections is a 0.16 M solution of sodium chloride. Calculate the mass in grams of sodium chloride needed to prepare 250. mL of solution.

7.45 Calculate the following for these common solutions found in clinics and hospitals:

a. The number of moles of dextrose (glucose) in 250. mL of a 0.278 M dextrose solution.

b. The number of grams of NaCl in 120. mL of a 0.154 M normal saline solution.

c. The number of grams of iodine in 20.0 mL of a 3.00% (w/v) tincture of iodine solution.

d. The number of milliliters of alcohol in 250. mL of a 90.0% (v/v) disinfectant solution.

7.46 Calculate the following:

a. The number of grams of Li_2CO_3 in 250. mL of 1.75 M Li_2CO_3 solution

b. The number of moles of NH_3 in 200. mL of 3.50 M NH_3 solution

c. The number of mL of alcohol in 250. mL of 12.5% (v/v) solution

d. The number of grams of $CaCl_2$ in 50.0 mL of 4.20% (w/v) $CaCl_2$ solution

7.47 Explain how you would prepare the following dilute solutions from the more concentrated ones:

a. 200. mL of 0.500 M HCl from a 6.00 M HCl solution

b. 50.0 mL of 2.00 M H_2SO_4 from a 6.00 M H_2SO_4 solution

c. 100. mL of normal saline solution, 0.89% (w/v) NaCl, from a 5.0% (w/v) NaCl solution

d. 250. mL of 5.00% (v/v) acetone from 20.5% (v/v) acetone

7.48 Explain how you would prepare the following dilute solutions from the more concentrated ones:

a. 5.00 L of 6.00 M H_2SO_4 from a 18.0 M H_2SO_4 solution

b. 250. mL of 0.500 M $CaCl_2$ from a 3.00 M $CaCl_2$ solution

c. 200. mL of 1.50% (w/v) KBr from a 10.0% (w/v) KBr solution

d. 500. mL of 10.0% (v/v) alcohol from 50.0% (v/v) alcohol

7.49 What is the molarity of the solution prepared by diluting 25.0 mL of 0.412 M $Mg(NO_3)_2$ solution to each of the following final volumes?

a. 40.0 mL

b. 0.100 L

c. 1.10 L

d. 350.0 mL

7.50 What is the molarity of the solution prepared by diluting 50.0 mL of 0.195 M KBr to each of the following volumes?

a. 1.50 L

b. 200. mL

c. 500. mL

d. 700. mL

Solution Stoichiometry (Section 7.6)

7.51 How many milliliters of 6.00 M HCl solution would be needed to react exactly with 20.0 g of pure solid NaOH?

$$HCl(aq) + NaOH(s) \rightarrow NaCl(aq) + H_2O(\ell)$$

7.52 How many grams of solid Na_2CO_3 will react with 250. mL of a 1.25 M HCl solution?

$$Na_2CO_3(s) + 2HCl(aq) \rightarrow 2NaCl(aq) + CO_2(g) + H_2O(\ell)$$

7.53 How many milliliters of 0.250 M HCl solution will exactly react with 10.5 g of solid $NaHCO_3$?

$$NaHCO_3(s) + HCl(aq) \rightarrow NaCl(aq) + CO_2(g) + H_2O(\ell)$$

7.54 How many milliliters of 0.250 M $AgNO_3$ solution will exactly react with 25.0 mL of a 0.200 M NaCl solution?

$$NaCl(aq) + AgNO_3(aq) \rightarrow NaNO_3(aq) + AgCl(s)$$

7.55 How many milliliters of 0.120 M Na_2S solution will exactly react with 35.0 mL of a 0.150 M $AgNO_3$ solution?

$$2AgNO_3(aq) + Na_2S(aq) \rightarrow Ag_2S(s) + 2NaNO_3(aq)$$

7.56 How many milliliters of 0.225 M NH_3 solution will exactly react with 30.0 mL of a 0.190 M H_2SO_4 solution?

$$2NH_3(aq) + H_2SO_4(aq) \rightarrow (NH_4)_2SO_4(aq)$$

7.57 How many milliliters of 0.124 M NaOH solution will exactly react with 35.0 mL of a 0.210 M H_3PO_4 solution?

$$3NaOH(aq) + H_3PO_4(aq) \rightarrow Na_3PO_4(aq) + 3H_2O(\ell)$$

7.58 How many milliliters of 0.124 M NaOH solution will exactly react with 25.0 mL of a 0.210 M HCl solution?

$$NaOH(aq) + HCl(aq) \rightarrow NaCl(aq) + H_2O(\ell)$$

7.59 How many milliliters of 0.115 M NaOH solution will exactly react with 25.0 mL of a 0.210 M H_2SO_4 solution?

$$2NaOH(aq) + H_2SO_4(aq) \rightarrow Na_2SO_4(aq) + 2H_2O(\ell)$$

7.60 Stomach acid is essentially 0.10 M HCl. An active ingredient found in a number of popular antacids is calcium carbonate, $CaCO_3$. Calculate the number of grams of $CaCO_3$ needed to exactly react with 250.0 mL of stomach acid.

$$CaCO_3(s) + 2HCl(aq) \rightarrow CO_2(g) + CaCl_2(aq) + H_2O(\ell)$$

7.61 An ingredient found in some antacids is magnesium hydroxide, $Mg(OH)_2$. Calculate the number of grams of $Mg(OH)_2$ needed to exactly react with 200. mL of stomach acid (see Exercise 7.60).

$$Mg(OH)_2(s) + 2HCl(aq) \rightarrow MgCl_2(aq) + 2H_2O(\ell)$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Solution Properties (Section 7.7)

7.62 Before it is frozen, ice cream is essentially a solution of sugar, flavorings, etc., dissolved in water. Use the idea of colligative solution properties and explain why a mixture of ice (and water) and salt is used to freeze homemade ice cream. Why won't just ice work?

7.63 If you look at the labels of automotive products used to prevent radiator freezing (antifreeze) and radiator boiling, you will find the same ingredient listed, ethylene glycol. Use the idea of colligative properties to explain how the same material can prevent an automobile cooling system from freezing and boiling.

7.64 Calculate the boiling and freezing points of water solutions that are 1.50 M in the following solutes:

a. KCl, a strong electrolyte

b. glycerol, a nonelectrolyte

c. $(NH_4)_2SO_4$, a strong electrolyte

d. $Al(NO_3)_3$, a strong electrolyte

7.65 Calculate the boiling and freezing points of water solutions that are 1.15 M in the following solutes:

a. KBr, a strong electrolyte

b. ethylene glycol, a nonelectrolyte

c. $(NH_4)_2CO_3$, a strong electrolyte

d. $Al_2(SO_4)_3$, a strong electrolyte

7.66 Calculate the boiling and freezing points of the following solutions. Water is the solvent, unless otherwise indicated.

a. A 0.50 M solution of urea, a nonelectrolyte

b. A 0.250 M solution of $CaCl_2$, a strong electrolyte

c. A solution containing 100. g of ethylene glycol ($C_2H_6O_2$), a nonelectrolyte, per 250. mL

7.67 Calculate the boiling and freezing points of the following solutions. Water is the solvent, unless otherwise indicated.

a. A solution containing 50.0 g of H_2SO_4, a strong electrolyte (both Hs dissociate), per 250. mL

b. A solution containing 200. g of table sugar ($C_{12}H_{22}O_{11}$), a nonelectrolyte, per 250. mL

c. A solution containing 75.0 g of octanoic acid ($C_8H_{16}O_2$), a nonelectrolyte, in enough benzene to give 250. mL of solution

7.68 Calculate the osmolarity for the following solutions:

a. A 0.15 M solution of glycerol, a nonelectrolyte

b. A 0.15 M solution of $(NH_4)_2SO_4$, a strong electrolyte

c. A solution containing 25.3 g of LiCl (a strong electrolyte) per liter

7.69 Calculate the osmolarity for the following solutions:

a. A 0.25 M solution of KCl, a strong electrolyte

b. A solution containing 15.0 g of urea (CH_4N_2O), a nonelectrolyte, per 500. mL

c. A solution containing 50.0 mL of ethylene glycol ($C_2H_6O_2$), a nonelectrolyte with a density of 1.11 g/mL, per 250. mL

Note: In Exercises 7.70–7.79, assume the temperature is 25.0°C, and express your answer in torr, mmHg, and atm.

7.70 Calculate the osmotic pressure of any solution with an osmolarity of 0.250.

7.71 Calculate the osmotic pressure of a 0.125 M solution of Na_2SO_4, a strong electrolyte.

7.72 Calculate the osmotic pressure of a 0.200 M solution of Na_2SO_4, a strong electrolyte.

7.73 Calculate the osmotic pressure of a 0.250 M solution of methanol, a nonelectrolyte.

7.74 Calculate the osmotic pressure of a solution that contains 95.0 g of the nonelectrolyte urea, CH_4N_2O, per 500. mL of solution.

7.75 Calculate the osmotic pressure of a solution that contains 1.20 mol of $CaCl_2$, a strong electrolyte, in 1.50 L.

7.76* Calculate the osmotic pressure of a solution that has a freezing point of 20.35ºC.

7.77* Calculate the osmotic pressure of a solution that is 0.122 M in solute and has a boiling point 0.19ºC above that of pure water.

7.78* Calculate the osmotic pressure of a solution that contains 5.30 g of NaCl and 8.20 g of KCl per 750. mL.

7.79 Calculate the osmotic pressure of a solution that contains 220.0 g of ethylene glycol ($C_2H_6O_2$), a nonelectrolyte, per liter.

7.80 Suppose an osmotic membrane separates a 5.00% sugar solution from a 10.0% sugar solution. In which direction will water flow? Which solution will become diluted as osmosis takes place?

Colloids (Section 7.8)

7.81 Explain how the following behave in a colloidal suspension: dispersing medium, dispersed phase, and colloid emulsifying agent.

7.82 Explain why detergents or soaps are needed if water is to be used as a solvent for cleaning clothes and dishes.

Dialysis (Section 7.9)

7.83 Suppose you have a bag made of a membrane like that in **Figure 7.26**. Inside the bag is a solution containing water and dissolved small molecules. Describe the behavior of the system when the bag functions as an osmotic membrane and when it functions as a dialyzing membrane.

7.84 Each of the following mixtures was placed in a dialysis bag like the one shown in **Figure 7.26**. The bag was immersed in pure water. Which substances will pass through the bag into the surrounding water?

a. NaCl solution and starch (colloid)

b. Urea (small organic molecule) and starch (colloid)

c. Albumin (colloid), KCl solution, and glucose solution (small organic molecule)

Additional Exercises

7.85 When 5.0 mL of water and 5.0 mL of rubbing alcohol are mixed together, the volume of the resulting solution is 9.7 mL. Explain in terms of molecules why the final solution volume is not 10.0 mL.

7.86 A student made a 7.00% (w/v) solution by dissolving 7.00 grams of sodium chloride (salt) in an appropriate volume of water. Assume the density of the water was 1.00 g/mL, and that there was no increase in volume when the salt was added to the water. Calculate the density of the resulting solution in g/mL.

7.87 Ethylene glycol is mixed with water and used as an antifreeze in automobile cooling systems. If a 50% (v/v) solution is made using pure ethylene glycol and pure water, it will have a freezing point of about −65°C. What will happen to the freezing point of the mixture if ethylene glycol is added until the concentration is 70% (v/v) ethylene glycol? Explain your answer.

7.88 How many mL of 1.50 M HCl solution contains enough HCl to react completely with 0.500 g of zinc metal? The reaction is $Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g)$.

7.89 At 20°C ethyl alcohol has a vapor pressure of 43.9 torr, and the vapor pressure of water at the same temperature is 17.5 torr. Suppose a 50% (v/v) solution of water and ethyl alcohol was brought to a boil and the first vapors given off were collected and condensed to a liquid. How would the percentage of alcohol in the condensed liquid compare to the percentage of alcohol in the original 50% solution (greater than, less than, equal to)? Explain your reasoning.

Chemistry for Thought

7.90 When a patient has blood cleansed by hemodialysis, the blood is circulated through dialysis tubing submerged in a bath that contains the following solutes in water: 0.6% NaCl, 0.04% KCl, 0.2% $NaHCO_3$, and 0.72% glucose (all percentages are w/v). Suggest one or more reasons why the dialysis tubing is not submerged in pure water.

7.91 Can the terms *saturated* and *supersaturated* be used to describe solutions made of liquids that are soluble in all proportions? Explain.

7.92 Refer to **Figure 7.4** and propose a reason why fish sometimes die when the temperature of the water in which they live increases.

7.93 Small souvenir salt-covered objects are made by forming the object out of wire mesh and suspending the mesh object in a container of water from a salt lake such as the Dead Sea or the Great Salt Lake. As the water evaporates, the wire mesh becomes coated with salt crystals. Describe this process using the key terms introduced in **Section 7.2**.

7.94 Refer to **Figure 7.9** and answer the question. How would the solubility of sugar compare in equal amounts of hot and iced tea?

7.95 Refer to **Figure 7.19** and explain the process as requested. Draw simple diagrams showing the initial appearance and appearance after some time for a similar experiment in which the two liquids are 0.20 M copper sulfate solution and 2.0 M copper sulfate solution. Explain your reasoning.

7.96 Strips of fresh meat can be preserved by drying. In one process, the strips are coated with table salt and exposed to the air. Use a process discussed in this chapter and one discussed in Chapter 6 to explain how the drying takes place.

8 Reaction Rates and Equilibrium

age fotostock/SuperStock

Health Career Focus

PHYSICIAN'S ASSISTANT

The hardest part is getting your patient experience. I'm lucky that I went to a high school that allowed students release time to attend a local technical college. I took advantage of that and earned a certificate in Medical Assisting by the time I graduated, so I worked at a doctor's office throughout college. The more intensive Physician Assistant program I completed later required 2000 hours of patient experience, but some require twice that!

I didn't decide to become a PA right away. I didn't even decide to go to college right away. I got married and started a family. I liked the Medical Assisting job but working with PAs helped me see more possibilities. I started dreaming about it, then I started planning for it.

My Physician Assistant program accepted online credit, and since I have kids, that made it much easier for me to meet the requirements. I could do my schoolwork for an hour or two after my children went to bed. It wasn't easy, but I'm so glad I did it. It's a lot of hard work, but if you want it, you'll find a way.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Use the concepts of energy and entropy to predict the spontaneity of processes and reactions. **(Section 8.1)**
2. Calculate reaction rates from experimental data. **(Section 8.2)**
3. Use the concept of molecular collisions to explain reaction characteristics. **(Section 8.3)**
4. Represent and interpret the energy relationships for reactions by using energy diagrams. **(Section 8.4)**
5. Explain how factors such as reactant concentrations, temperature, and catalysts influence reaction rates. **(Section 8.5)**
6. Relate experimental observations to the establishment of equilibrium. **(Section 8.6)**
7. Write equilibrium expressions based on reaction equations, and do calculations based on equilibrium expressions. **(Section 8.7)**
8. Use Le Châtelier's principle to predict the influence of changes in concentration and reaction temperature on the position of equilibrium for reactions. **(Section 8.8)**

ACCORDING TO CALCULATIONS, carbon in the form of a diamond will spontaneously change into graphite. Owners of diamonds seem unconcerned by this fact; they know from experience that their investments in gems are secure. In reality, the change does take place, but occurs so slowly that it is not detectable over many human lifetimes. The low rate of the reaction makes the difference.

The element barium is very poisonous when it is taken into the body as barium ions (Ba^{2+}). When barium sulfate ($BaSO_4$) dissolves, Ba^{2+} and $SO_4{}^{2-}$ ions are formed. However, suspensions of solid $BaSO_4$ are routinely swallowed by patients undergoing diagnostic X-ray photography of the stomach and intestinal tract. The patients are not affected because very little $BaSO_4$ dissolves in the body. This lack of solubility is an equilibrium property of $BaSO_4$.

Skitterphoto/2307 images/Pixabay

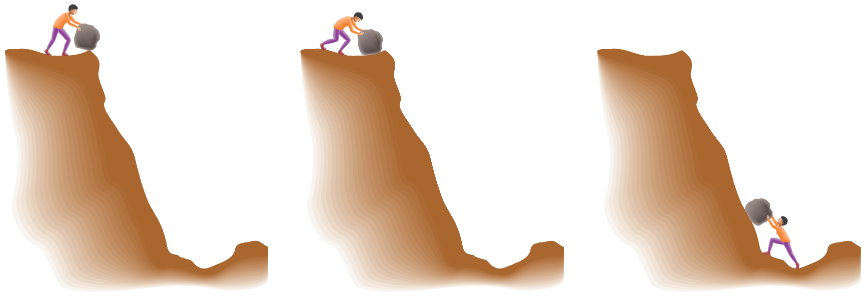
FIGURE 8.1 The rusting of iron is a spontaneous process.

8.1 Spontaneous and Nonspontaneous Processes

Learning Objective 1 Use the concepts of energy and entropy to predict the spontaneity of processes and reactions.

Years ago, tourists in Salt Lake City visited "gravity hill," where an optical illusion made a stream of water appear to flow uphill. The fascination with the scene came from the apparent violation of natural laws—everyone knew that water does not flow uphill. Processes that take place naturally with no apparent cause or stimulus are called **spontaneous processes** (see **Figure 8.1**). Nonspontaneous processes take place only as the result of some cause or stimulus. For example, imagine you are in the positions depicted in **Figure 8.2** and want to move a boulder.

spontaneous process A process that takes place naturally with no apparent cause or stimulus.



a Spontaneous process

b Spontaneous process once started

c Nonspontaneous process

FIGURE 8.2 The problem of moving a boulder.

In part (a), the boulder will roll down the hill as soon as you release it; the process begins and takes place spontaneously. In part (b), you must push the boulder a little to get it over the hump, but once started, the boulder spontaneously rolls downhill. The situation in part (c) is very different. You must continually push on the boulder, or it will not move up the hill; at no time can you stop pushing and expect the boulder to continue moving up. The process is nonspontaneous; it takes place only because of the continuous application of an external stimulus.

As the boulder rolls downhill, it gives up energy; it moves from a state of high potential energy to a lower one. As you push the boulder uphill, it gains energy (from you).

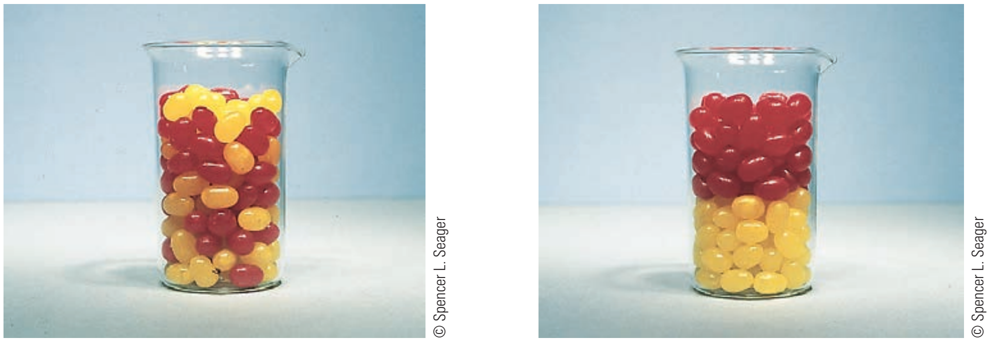
exergonic process A process that gives up energy as it takes place.

endergonic process A process that gains or accepts energy as it takes place.

Processes that give up energy are called **exergonic** (energy out), whereas those that gain energy are called **endergonic** (energy in). Very often, energy changes in chemical processes involve heat. Those changes that do are referred to as either exothermic (heat out) or endothermic (heat in), two terms you have encountered before (see **Sections 5.8** and **6.11**).

entropy A measurement or indication of the disorder or randomness of a system. The more disorderly a system is, the higher its entropy.

Many spontaneous processes give up energy. A piece of wood, once ignited, spontaneously burns and liberates energy as heat and light. At normal room temperature, steam spontaneously condenses to water and releases heat. However, some spontaneous processes take place and either give up no energy or actually gain energy. These spontaneous processes are always accompanied by another change called an entropy increase. **Entropy** describes the disorder or mixed-up character (randomness) of a system (see **Figure 8.3**). Thus, an entropy increase accompanies all spontaneous processes in which energy remains constant or is gained. A drop of ink placed in a glass of water will eventually become uniformly distributed throughout the water, even though the water is not stirred. No energy change accompanies the diffusion of the ink, but the distribution of ink throughout the water is a more disorderly (higher-entropy) state than when the ink is all together in a single drop. Ice melts spontaneously at 20°C and in the process absorbs heat. The process takes place because the random distribution of water molecules in the liquid is in a higher-entropy state than the orderly molecular arrangement found in crystalline ice.


© Spencer L. Seager

© Spencer L. Seager

FIGURE 8.3 The mixture on the left has higher entropy (more randomness, or mixed-up character) than the mixture on the right.

Energy and entropy changes influence the spontaneity of processes in several ways:

1. A process will always be spontaneous if the energy decreases and the entropy increases. An example of such a process is the burning of a piece of wood, in which heat is given up and the gaseous products of combustion are distributed throughout the surroundings, enabling the entropy to increase.
2. When a spontaneous process is accompanied by an energy increase, a large entropy increase must also occur. Thus, when ice spontaneously melts at 20°C, the increase in entropy is large enough to compensate for the increase in energy that also takes place.
3. A spontaneous process accompanied by an entropy decrease must also be accompanied by a compensating energy decrease. Thus, when water spontaneously freezes at 0°C, the energy loss compensates for the entropy decrease that occurs as the water molecules assume the well-ordered arrangement in ice.

stable substance A substance that does not undergo spontaneous changes under the surrounding conditions.

It is useful to think of energy and entropy changes in terms of the directions favoring spontaneity and the directions not favoring spontaneity. It is apparent from the preceding discussion that spontaneity is favored by an energy decrease and/or an entropy increase. Processes in which one of these factors changes in a nonspontaneous direction will be spontaneous only if the other factor changes in a spontaneous direction by a large enough amount to compensate for the nonspontaneous change. The influences listed under 2 and 3 above are examples of this.

A substance that does not undergo spontaneous changes is said to be a **stable substance** (see **Figure 8.4**). However, stability depends on the surrounding conditions, and a change in those conditions might cause a nonspontaneous process to become spontaneous. Ice is a stable solid at −10°C and 760 torr pressure but spontaneously melts to a liquid at 5°C and 760 torr. Wood is stable at room temperature but spontaneously burns when its temperature equals or exceeds the ignition temperature. In the following discussions, the surrounding conditions are assumed to be those normally encountered. Otherwise, the differences are specified.

Ukki Studio/Shutterstock.com

FIGURE 8.4 Both gold and diamonds are valuable because of their beauty and their stability.

8.2 Reaction Rates

Learning Objective 2 Calculate reaction rates from experimental data.

reaction rate The speed of a reaction.

The speed of a reaction is called the **reaction rate**. It is determined experimentally as the change in concentration of a reactant or product divided by the time required for the change to occur. This average rate is represented for changes in product concentration in Equation 8.1:

$$\text{Rate} = \frac{\Delta C}{\Delta t} = \frac{C_t - C_0}{\Delta t} \qquad (8.1)$$

where the delta symbol (Δ) stands for change. C_t and C_0 are the concentrations of a product at the end and beginning of the reaction, respectively, of the measured time change, Δt. The time can be measured in any convenient unit.

Example 8.1 Calculating Reaction Rates

Nitric oxide, NO, is used in hospitals for lung vasodilation of preterm newborns and patients with pulmonary distress.

The gases NO_2 and CO react as follows:

$$NO_2(g) + CO(g) \longrightarrow NO(g) + CO_2(g)$$

Calculate the average rate of the reaction if pure NO_2 and CO are mixed and after 50.0 seconds the concentration of CO_2 is found to be 0.0160 mol/L.

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: the balanced reaction; concentration of CO_2 after 50.0 seconds = 0.0160 mol/L

Unknown: average rate of reaction = ?

STEP 2 Identify a formula that links the known and unknown terms.

$$\text{Equation 8.1: } \frac{\Delta C}{\Delta T} = \frac{C_t - C_0}{\Delta t}$$

STEP 3 Enter the data into the formula.

Because the reaction was started by mixing pure NO_2 and CO, the initial concentration C_0 of CO_2 was 0.000 mol/L. After 50.0 seconds, the concentration C_t of CO_2 was 0.0160 mol/L.

$$\text{Rate} = \frac{C_t - C_0}{\Delta t} = \frac{0.0160\text{ mol/L} - 0.000\text{ mol/L}}{50.0\text{ s}} = 3.20 \times 10^{-4}\,\frac{\text{mol/L}}{\text{s}}$$

The answer is 3.20×10^{-4} mol per liter per second, meaning that during the 50.0 second time interval, an average of 3.20×10^{-4} mol CO_2 was formed in each liter of reacting mixture each second.

STEP 4 Check to see whether the answer makes sense.

Yes. The answer has the correct units and the correct number of significant figures, and the value seems reasonable.

✔ **LEARNING CHECK 8.1** The Ce^{4+} and Fe^{2+} ions react in solution as follows:

$$Ce^{4+}(aq) + Fe^{2+}(aq) \longrightarrow Ce^{3+}(aq) + Fe^{3+}(aq)$$

Solutions of Ce^{4+} and Fe^{2+} are mixed and allowed to react. After 75.0 seconds, the concentration of Ce^{3+} is found to be 1.50×10^{-5} mol/L. Calculate the average rate of the reaction.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

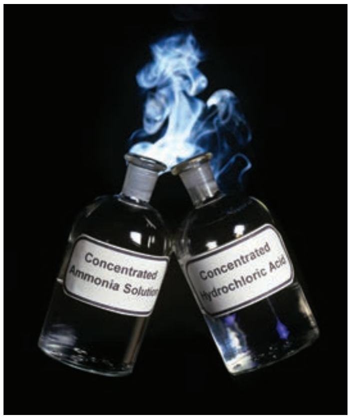
8.3 Molecular Collisions

Learning Objective 3 Use the concept of molecular collisions to explain reaction characteristics.

Chemical equations such as those in Example 8.1 and Learning Check 8.1 are useful in identifying reactants and products and in representing the stoichiometry of a reaction. However, they indicate nothing about how a reaction takes place—how reactants get together (or break apart) to form products. The explanation of how a reaction occurs is called a **reaction mechanism**. Reaction mechanisms are not discussed much in this book, but most are based on the following assumptions:

reaction mechanism A detailed explanation of how a reaction actually takes place.

1. Reactant particles must collide with one another in order for a reaction to occur.
2. Particles must collide with at least a certain minimum total amount of energy if the collision is to result in a reaction.
3. In some cases, colliding reactants must be oriented in a specific way if a reaction is to occur.



Martyn F. Chillmaid/Science Source

FIGURE 8.5 The gases HCl and NH_3 react to form a white cloud of NH_4Cl (ammonium chloride) as the two bottles are brought close together.

The validity of the first assumption is fairly obvious. Two molecules cannot react with each other if they are far apart. In order to break bonds, exchange atoms, and form new bonds, they must come in contact. There are, however, some exceptions, such as decompositions in which molecules break into fragments and processes in which molecules react by an internal rearrangement of their atoms.

In general, reactions take place more rapidly in the gaseous or liquid state than in the solid state (see **Figure 8.5**). This observation verifies the first assumption because molecules of gases and liquids move about freely and can undergo many more collisions than can the rigidly held molecules of solids. Reactions involving solids usually take place only on the solid surface and therefore involve only a small fraction of the total molecules present in the solid. As the reaction proceeds and the products dissolve, diffuse, or fall from the surface, fresh solid is exposed. In this way, the reaction proceeds into the solid. The rusting of iron is an example of such a process.

If collisions were the only factor, then, most gaseous and liquid state reactions would take place almost instantaneously if every collision results in a reaction. Such high reaction rates are not observed, a fact that brings us to assumptions 2 and 3.

internal energy The energy associated with vibrations within molecules.

activation energy Energy needed to start some spontaneous processes. Once started, the processes continue without further stimulus or energy from an outside source.

One of the ways to speed up a chemical reaction is to add energy in the form of heat. The added heat increases both the average speed (kinetic energy) and the internal energy of the molecules. **Internal energy** is the energy associated with molecular vibrations. An increase in internal energy increases the amplitude of molecular vibrations and, if large enough, breaks bonds (see **Figure 8.6**). Internal energy is also increased by the conversion of some kinetic energy into internal energy during collisions. When heat is added, both the kinetic and the internal energy of molecules is increased. This increases the frequency and speed of collisions and the chances that a collision will cause a sufficient increase in internal energy to break bonds and bring about a reaction (see **Figure 8.7**).

In some reaction mixtures, the average total energy of the molecules is too low at the prevailing temperature for a reaction to proceed at a detectable rate; the reaction mixture is stable. However, some reactions can be started by providing **activation energy**. Once the reaction is started, enough energy is released to activate other molecules and keep the reaction going at a good rate. The energy needed to get the boulder over the small hump in **Figure 8.2(b)** is a kind of activation energy. In many chemical reactions, activation energy causes bonds in reactant molecules to break. When the broken bonds react to form the new bonds of the products, energy is released that can cause bonds in more reactant molecules to break and the reaction to continue. The striking of a kitchen match is a good example. Activation energy is provided by rubbing the match head against a rough surface. Once started, the match continues to burn spontaneously.

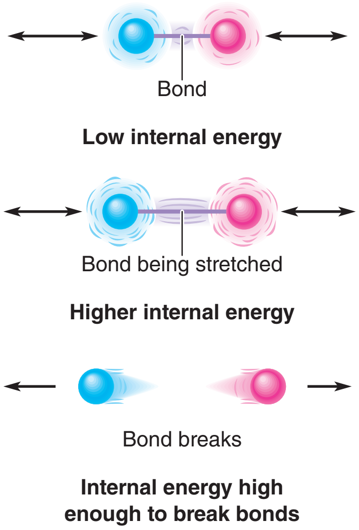


FIGURE 8.6 The internal energy of molecules.

A number of gases are routinely used in hospitals. Some of these form very flammable or even potentially explosive mixtures. Cyclopropane, a formerly used anesthetic, will burn vigorously in the presence of the oxygen in air. However, a mixture of the two will not react unless activation energy is provided in the form of an open flame or a spark. This is the reason that extreme precautions are taken to avoid open flames and sparks in a

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS 8.1

Energy Drinks

This feature will focus on energy drinks.

It is difficult to lump all energy drinks together because different products contain different proprietary blends of ingredients, but they all contain some stimulant(s), most often caffeine. Naturally caffeinated drinks (tea or coffee) are usually not considered to be "energy drinks." Typical popular soft drinks that contain 20–50 mg of caffeine per 12 oz serving are also not considered to be energy drinks in this discussion.

Other common ingredients of energy drinks include amino acids (taurine and carnitine), vitamins (in nominal amounts that have little/no benefit), carbohydrates, and herbal extracts (ginseng, guarana, yerba maté, and ginkgo biloba in variable amounts that are unregulated in spite of having numerous interactions with drugs).

Even though the amount of caffeine in a typical energy drink is not more per ounce than brewed coffee, the marketed container size of energy drinks is much larger than a cup of coffee, and most consumers drink the entire can. This means that the total amount of caffeine consumed will have both good and bad pharmacological effects.

The good effects include increased mental alertness at work or school, since caffeine stimulates the central and autonomic nervous systems. This combats fatigue while driving, and might help prevent auto accidents.

The possible bad effects are as follows:

- Causes nervousness, irritability, anxiety, and phobias.
- Causes insomnia. Might be more difficult to fall asleep and stay asleep and result in less deep sleep.
- Causes rapid heartbeat. Can induce dysrhythmias, heart attacks, and death.
- Causes increased blood pressure, gastrointestinal distress, and muscle tremors.

Energy drinks are often consumed before exercise or athletic events. The additional fluid intake is healthful, but be aware that caffeine is a diuretic that might increase the risk of dehydration.

Recommendations:

1. If you consistently lack energy, consider healthier alternatives such as scheduling an additional 10–15 minutes of sleep each night.
2. Eat a healthful diet and follow a regular exercise/recreation program.
3. Evaluate the amount and quality of sleep you get. Energy drinks that help you get through the day might interfere with your sleep architecture and actually decrease the quality and quantity of your sleep. That leads to a vicious cycle.
4. If you intend to decrease your energy drink consumption for any reason, do not stop abruptly. An abrupt stop might cause withdrawal symptoms such as headache and fatigue.

Chuck Wagner/Shutterstock.Com

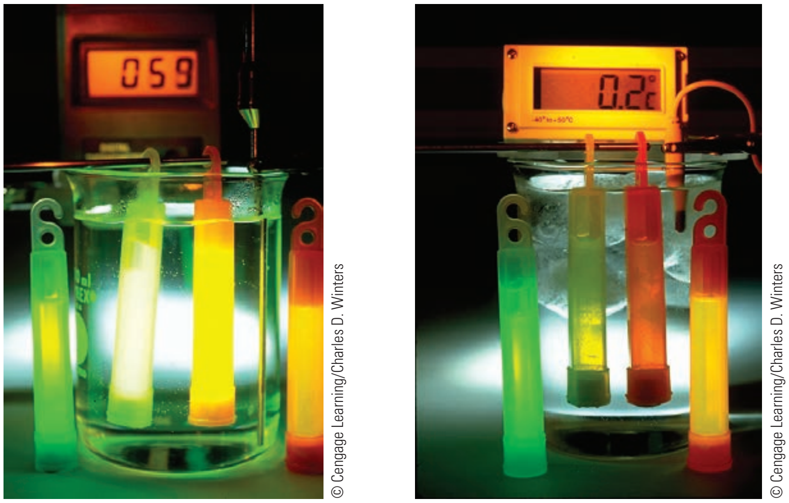
There are both pros and cons to consuming energy drinks.

hospital operating room. Even sparks from static electricity can set off such gaseous mixtures, so special materials are used in clothing, floor coverings, and so on to prevent static electricity from building up.

Oxygen gas does not burn, but it reacts with anything that is combustible. Oxygen is often used in hospitals in concentrations much higher than the 20% found in air. Thus, precautions must be taken to prevent fire or sparks in any areas where oxygen gas is used in high concentrations.

Orientation effects are related to which side or end of a particle actually hits another particle during a collision. Orientation effects are unimportant in many reactions. For example, the orientation of silver ions (Ag^+) and chloride ions (Cl^-) toward each other during a collision has no effect on the rate of forming AgCl:

$$Ag^+(aq) + Cl^-(aq) \longrightarrow AgCl(s) \qquad (8.2)$$



© Cengage Learning/Charles D. Winters

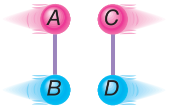
© Cengage Learning/Charles D. Winters

FIGURE 8.7 The reaction that makes a Cyalume light stick glow takes place more rapidly in hot water (left) than in ice water (right). The light sticks outside the container are at room temperature. Which pair of sticks would glow for a longer time? Explain your reasoning.

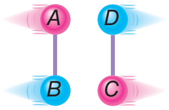
The reason is that Ag^+ and Cl^- are both essentially spherical charged particles. However, collision orientation may be important in reactions that involve nonspherical molecules (assumption 3). Consider the following hypothetical reaction:

$$A\text{—}B + C\text{—}D \rightarrow A\text{—}C + B\text{—}D \tag{8.3}$$

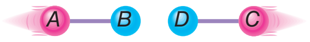
It is clear that the collision orientation of *A*—*B* and *C*—*D* shown in **Figure 8.8(a)** is more favorable to reaction than the orientations shown in **Figures 8.8(b)** and **8.8(c)**.



a Favorable orientation: *A* is near *C*, and *B* is near *D* during collision.



b Unfavorable orientation: *A* is not near *C*, and *B* is not near *D* during collision.



c Unfavorable orientation: *B* is near *D*, but *A* and *C* are far removed during collision.

FIGURE 8.8 Molecular orientations during collisions.

8.4 Energy Diagrams

Learning Objective 4 Represent and interpret the energy relationships for reactions by using energy diagrams.

Energy relationships for reactions can be represented by energy diagrams like the one in **Figure 8.9**. Notice the similarity to the earlier example of rolling boulders.

The energy diagrams for most reactions look generally alike, but there are some differences. Typical diagrams for exothermic (exergonic) and endothermic (endergonic) reactions are given in **Figure 8.10**. It is clear that the products of exothermic reactions have lower energy than the reactants and that the products of endothermic reactions have higher energy than the reactants. When exothermic reactions occur, the energy difference between reactants and products is released. This energy often appears as

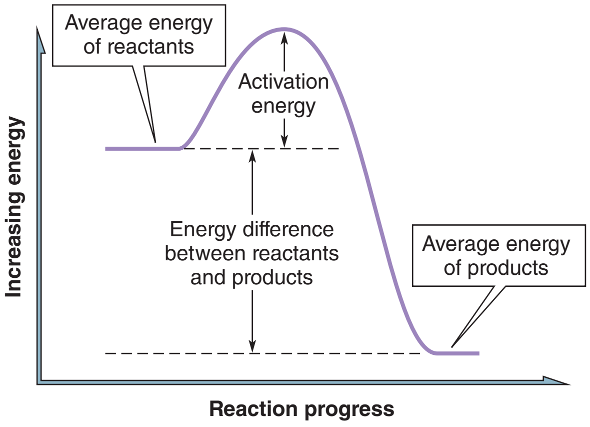

Average energy of reactants
Activation energy
Energy difference between reactants and products
Average energy of products
Increasing energy
Reaction progress

FIGURE 8.9 A typical energy diagram for chemical reactions.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

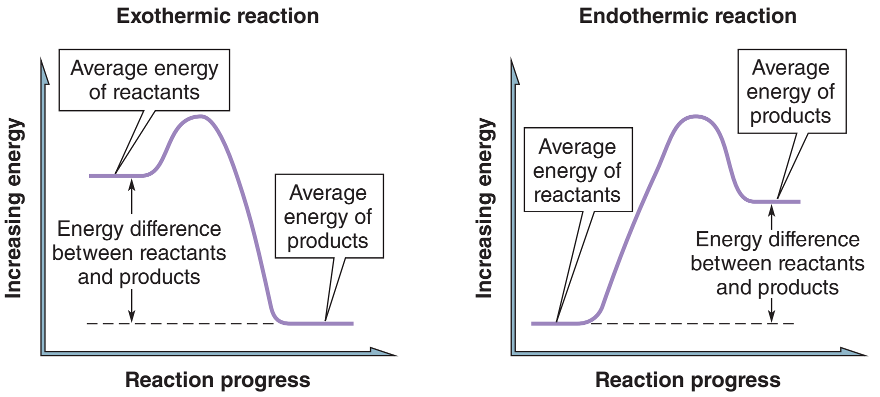

Exothermic reaction
Average energy of reactants
Energy difference between reactants and products
Average energy of products
Increasing energy
Reaction progress
Endothermic reaction
Average energy of products
Average energy of reactants
Energy difference between reactants and products
Increasing energy
Reaction progress

FIGURE 8.10 Energy diagrams for exothermic and endothermic reactions.

heat, so heat is given up to the surroundings. When endothermic reactions occur, the energy (heat) added to the products is absorbed from the surroundings. Also, different reactions generally have different activation energies, a fact easily represented by energy diagrams.

White phosphorus, a nonmetallic element, spontaneously bursts into flame if left in a rather warm room (34°C):

$$4P(s) + 5O_2(g) \longrightarrow P_4O_{10}(s) \qquad (8.4)$$

Sulfur, another nonmetallic element, will also burn, but it does not ignite until heated to about 232°C:

$$S(s) + O_2(g) \longrightarrow SO_2(g) \qquad (8.5)$$

The different activation energies for these two exothermic reactions are represented in **Figure 8.11**.

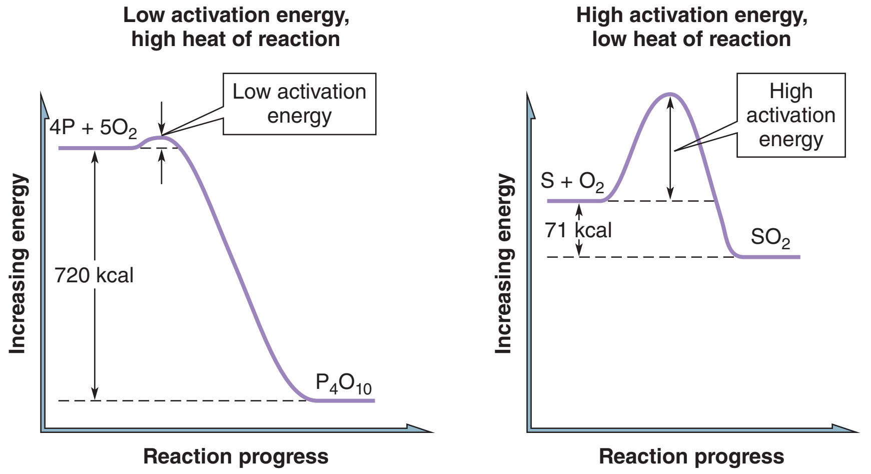

Low activation energy, high heat of reaction
Low activation energy
4P + 5O2
720 kcal
P4O10
Increasing energy
Reaction progress
High activation energy, low heat of reaction
High activation energy
S + O2
71 kcal
SO2
Increasing energy
Reaction progress

FIGURE 8.11 Differences in activation energies.

It should now be clear why we stressed the notion that some substances that are "stable" at normal living conditions undergo spontaneous changes at other conditions. It is simply that a higher temperature would provide the necessary activation energy. In a room hotter than 232°C, for example, both white phosphorus and sulfur would be "unstable" in the presence of oxygen.

8.5 Factors That Influence Reaction Rates

Learning Objective 5 Explain how factors such as reactant concentrations, temperature, and catalysts influence reaction rates.

Reaction rates are influenced by a number of different factors. Four factors that affect the rates of all reactions are:

1. The nature of the reactants.
2. The concentration of the reactants.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

3. The temperature of the reactants.
4. The presence of catalysts.

The formation of insoluble AgCl by mixing together solutions containing Ag^+ and Cl^- ions is represented by Equation 8.2, given earlier. The white solid AgCl forms the instant the two solutions are mixed. This behavior is typical of reactions involving ionic reactants. The high reaction rate results from the attraction of the charged reactants to each other. In contrast, reactions that require covalent bonds to be broken or formed often proceed slowly. The production of water gas, a mixture of hydrogen (H_2) and carbon monoxide (CO), is a reaction involving covalent bonds:

$$H_2O(g) + C(s) \xrightarrow{\text{Heat}} CO(g) + H_2(g) \qquad (8.6)$$

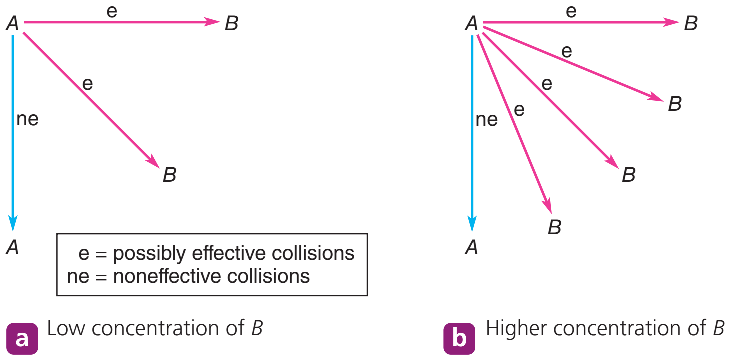
In addition, other structural characteristics of reactants, such as bond polarity or molecular size, may also be important factors in reaction rates.

The influence of reactant concentration on reaction rates can be illustrated by using the concept of molecular collisions. Suppose a reaction takes place between the hypothetical molecules *A* and *B*, which are mixed in a 1:1 ratio. The proposed reaction is

effective collision A collision that causes a reaction to occur between the colliding molecules.

$$A + B \rightarrow \text{products} \qquad (8.7)$$

Collisions with the capability to cause a reaction to occur are called **effective collisions**. Only collisions between *A* and *B* molecules can be classified as effective, since collisions between two *A* molecules or between two *B* molecules cannot possibly yield products. Imagine the reaction is begun with two *A* molecules and two *B* molecules as shown in **Figure 8.12**. The example is simplified by looking only at the collisions of a single *A* molecule. Initially, two of every three collisions of the *A* molecule will be effective (part (a)). On doubling the number (concentration) of *B* molecules, the number of effective collisions also doubles, and four of every five collisions is effective (part (b)).


A
e
B
e
ne
B
A
e = possibly effective collisions
ne = noneffective collisions
A
e
B
e
e
e
B
ne
B
B
A
a
b

a Low concentration of *B*

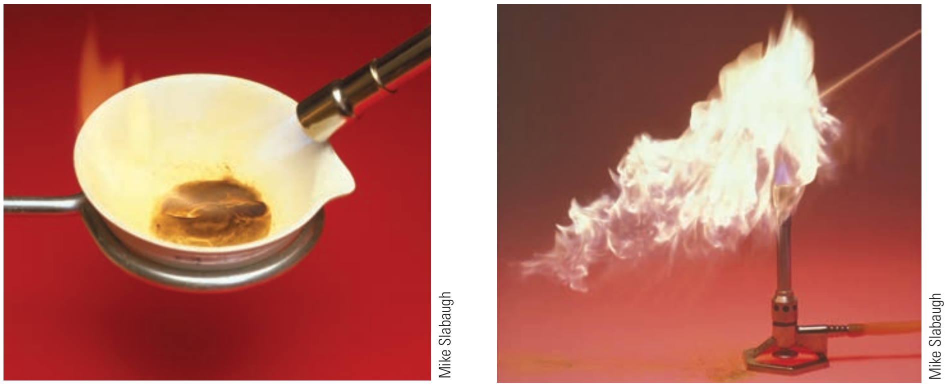
b Higher concentration of *B*

FIGURE 8.12 The effect of concentration on reaction rates.

When larger numbers of molecules are used, the results approach more closely those actually observed experimentally for simple chemical reactions. Imagine a mixture containing 1000 *A* molecules and 1000 *B* molecules. On the average, 1000 out of every 1999 collisions of a single *A* molecule will involve a *B* molecule. (Each *A* molecule has almost a 50–50 chance of bumping into a *B* molecule.) This gives essentially a 1:1 ratio of effective to noneffective collisions. When the number of *B* molecules is doubled to 2000, the ratio becomes 2:1, because 2000 of every 2999 collisions will be effective. Therefore, the reaction rate should double when the concentration of one reactant is doubled. This result has been verified in numerous chemical reactions. Thus, higher concentrations produce a larger number of effective collisions in a given period of time, and this increases the reaction rate.

Gas-phase reactions are easily visualized this way, but reacting liquids and solids must be looked at differently. A large piece of solid contains a large number of molecules, but, as described before, only those on the surface can react with the molecules of another substance. For this reason, the total amount of solid in a sample is not as important as the surface area of solid in contact with other reactants. The effective concentration of a solid therefore depends on its surface area and state of division. A 100-pound sack of flour is difficult to burn when

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.


Mike Slabaugh

Mike Slabaugh

1 A compact pile of lycopodium powder burns sluggishly.

2 A similar sample of lycopodium powder is blown through a blowpipe. The blown powder burns instantly with a bright flash.

FIGURE 8.13 Surface area influences reaction rates of solids. What is the other reactant in this reaction? How finely divided is it?

it is in a single pile. The same 100 pounds dispersed in the air as a fine dust burns very rapidly, and a dust explosion results (see **Figure 8.13**). The effective concentrations of reacting liquids must be thought of in a similar way unless the reactants are completely miscible.

The effect of reactant temperature on reaction rates can also be explained by using the molecular collision concept. As was noted earlier, an increase in the temperature of a system increases the average kinetic energy and internal energy of the reacting molecules. The increased molecular speed (kinetic energy) causes more collisions to take place in a given time. Also, because the kinetic and internal energies of the colliding molecules are greater, a larger fraction of the collisions will be effective because they will provide the necessary activation energy.

As a rough rule of thumb, it has been found that the rate of a chemical reaction doubles for every 10°C increase in temperature. The chemical reactions of cooking take place faster in a pressure cooker because of a higher cooking temperature (see **Section 6.13**). Also, cooling or freezing is used to slow the chemical reactions involved in the spoiling of food, souring of milk, and ripening of fruit.

A **catalyst** is a substance that changes reaction rates without being used up in the reactions. Usually the term *catalyst* is used to describe substances that speed up reactions. A substance that slows reactions is know as an **inhibitor**. Catalysts are used in a number of different forms. Those dispersed uniformly throughout a reaction mixture in the form of individual ions or molecules are called **homogeneous catalysts**. **Heterogeneous,** or **surface catalysts** are used in the form of solids; usually they have large surface areas on which reactions take place readily.

catalyst A substance that changes (usually increases) reaction rates without being used up in the reaction.

inhibitor A substance that decreases reaction rates.

homogeneous catalyst A catalytic substance that is distributed uniformly throughout the reaction mixture.

heterogeneous (surface) catalyst A catalytic substance normally used in the form of a solid with a large surface area on which reactions take place.

Catalysts enhance a reaction rate by providing an alternate reaction pathway that requires less activation energy than the normal pathway. This effect is represented by **Figure 8.14**. According to some theories, a catalyst provides the lower-energy pathway by entering into a reaction and forming an intermediate structure, which then breaks up to produce the final products and regenerate the catalyst:

$$\textbf{Uncatalyzed:} \qquad A + B \rightarrow \text{products} \qquad (8.8)$$

$$\textbf{Catalyzed:} \qquad A + B + \text{catalyst} \rightarrow \underset{\text{catalyst}}{\underset{|\quad\;\; |}{A - B}} \rightarrow \text{products} + \text{catalyst} \qquad (8.9)$$

Intermediate structure

According to another proposed mechanism, solid catalysts provide a surface to which reactant molecules become attached with a particular orientation. Reactants attached to these surfaces are sufficiently close to one another and oriented favorably enough to allow the reaction to take place. The products of the reaction then leave the surface and make the attachment sites available for catalyzing other reactant molecules.

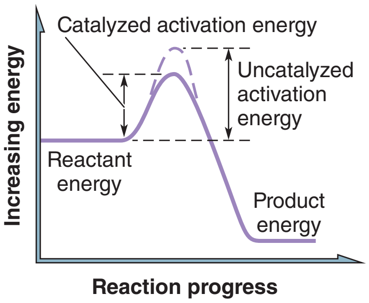


FIGURE 8.14 The effect of catalysts on activation energy.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS 8.2

Use Your Phone to Help You Stay Healthy

In the early days of cell phone technology, some feared that radiation from the phone could negatively impact the health of the user, or that overuse would lead to mental inactivity. Medical doctors no longer recommend turning off your cell phone to protect your health. Now, with smartphones, users are finding ways that their phones can help preserve and improve their health. The following are three health-oriented cell phone applications:

1. **Emergencies:** Cell phones are an important tool to help users in case of an emergency. A variety of features are offered, including the voice-activated dialing of 911 and pinpointing your location and providing first responders with critical background health information.
2. **Fitness Training:** Cell phones often come preloaded with health applications that monitor and record activities such as walking, running, and cycling. There are applications that can monitor your heart rate and blood oxygen saturation levels. Caloric and sleep tracking are even possible with certain applications, keeping you healthy, as well as connected and entertained.
3. **Medical ID:** Cell phones can function as a complex medical ID, with much more information than can be included on a traditional ID bracelet. Phone users can enter all sorts of pertinent medical information on the health app, including blood type, drug or food allergies, important medications or medical conditions, and other lifesaving information. Any savvy phone user (including paramedics) can access this emergency information.

iStock.com/AndreyPopov

Some phones support an app that can monitor your heart rate.

8.6 Chemical Equilibrium

Learning Objective 6 Relate experimental observations to the establishment of equilibrium.

So far, the focus has been only on the reactants of a reaction. However, all reactions can (in principle) go in both directions, and the products can be looked on as reactants. Suppose equal amounts of gaseous H_2 and I_2 are placed in a closed container and allowed to react and form HI. Initially, no HI is present, so the only possible reaction is

$$H_2(g) + I_2(g) \longrightarrow 2HI(g) \qquad (8.10)$$

However, after a short time, some HI molecules are produced. They can collide with one another in a way that causes the reverse reaction to occur:

$$2HI(g) \longrightarrow H_2(g) + I_2(g) \qquad (8.11)$$

The low concentration of HI makes this reaction slow at first, but as the concentration increases, so does the reaction rate. The rate of reaction decreases as the concentrations of H_2 and I_2 decrease. Eventually, the concentrations of H_2, I_2, and HI in the reaction mixture reach levels at which the rates of the forward (Equation 8.10) and reverse (Equation 8.11) reactions are equal. From that time on, the concentrations of H_2, I_2, and HI in the mixture remains constant, since both reactions take place at the same rate and each substance is being produced as fast as it is used up. When the forward and reverse reaction rates are equal, the reaction is in a **state of equilibrium**, and the concentrations are called **equilibrium concentrations**. The behavior of reaction rates and reactant concentrations for both the forward and reverse reactions is shown graphically in **Figure 8.15**.

state of equilibrium A condition in a reaction system when the rates of the forward and reverse reactions are equal.

equilibrium concentrations The unchanging concentrations of reactants and products in a reaction system that is in a state of equilibrium.

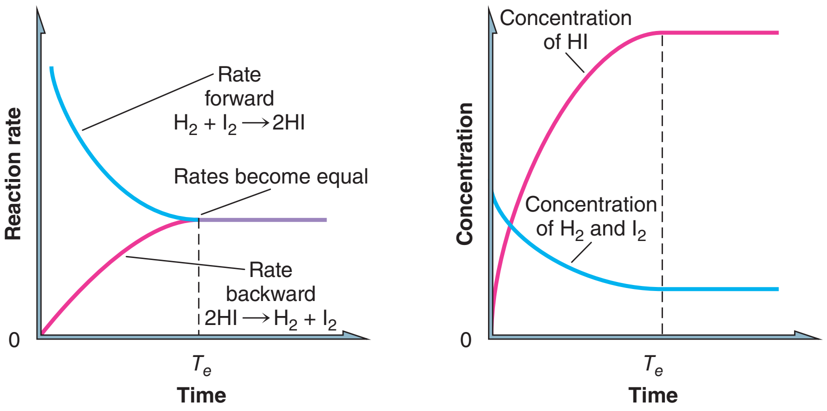


FIGURE 8.15 Variation of reaction rates and reactant concentrations as equilibrium is established (T_e is the time needed to reach equilibrium).

Instead of writing separate equations for both the forward and reverse reactions, the usual practice is to represent reversibility by double arrows. Thus, the equation for the reaction between H_2 and I_2 is written as

$$H_2(g) + I_2(g) \rightleftarrows 2HI(g) \tag{8.12}$$

8.7 The Position of Equilibrium

Learning Objective 7 Write equilibrium expressions based on reaction equations, and do calculations based on equilibrium expressions.

The **position of equilibrium** for a reaction indicates the relative amounts of reactants and products present at equilibrium. When the position is described as being far to the right, it means that at equilibrium the concentration of products is much higher than the concentration of reactants. A position far to the left means the concentration of reactants is much higher than that of products.

position of equilibrium An indication of the relative amounts of reactants and products present at equilibrium.

The position of equilibrium can be represented numerically by using the concept of an equilibrium constant. Any reaction that establishes an equilibrium can be represented by a general equation:

$$aA + bB + \cdots \rightleftarrows wW + xX + \cdots \tag{8.13}$$

In this equation, the capital letters stand for substances such as the H_2, I_2, and HI of Equation 8.12, and the lowercase letters are the coefficients in the balanced equation such as the 1, 1, and 2 of Equation 8.12. The dots in Equation 8.13 indicate that any number of reactants and products can be involved in the reaction, but we will limit ourselves to just the four shown.

As we implied earlier, a reaction at equilibrium can be recognized because the concentrations of reactants and products remain constant. That is, they do not change as time passes. For a reaction at equilibrium, the following equation is valid:

$$K = \frac{[W]^w[X]^x}{[A]^a[B]^b} \tag{8.14}$$

In this **equilibrium expression**, the brackets [ ] represent molar concentrations of the reactants (A and B) and the products (W and X). The K is a constant called the **equilibrium constant**, and the powers on each bracket are the coefficients from the balanced equation for the reaction. According to this equation, the product of equilibrium concentrations of products (raised to appropriate powers) divided by the product of the equilibrium concentration of reactants (also raised to appropriate powers) gives a number that does not change with time (the equilibrium constant). The reason K does not change with time is that at equilibrium, the concentrations used to calculate K do not change with time. We could get a different constant by dividing the reactant concentrations by the product concentrations, but it is the accepted practice to calculate K values as we have shown in Equation 8.14.

equilibrium expression An equation relating the equilibrium constant and reactant and product equilibrium concentrations.

equilibrium constant A numerical relationship between reactant and product concentrations in a reaction at equilibrium.

Example 8.2 Writing Equilibrium Expressions

An understanding of equilibrium expressions is very important in biological processes such as the transport of oxygen by hemoglobin.

Write equilibrium expressions for the reactions represented by the following equations:

a. $H_2(g) + I_2(g) \rightleftarrows 2HI(g)$
b. $2SO_2(g) + O_2(g) \rightleftarrows 2SO_3(g)$

Solution

a. The concentration of the product HI goes on top and is raised to the power 2. The concentrations of the reactants H_2 and I_2 go on the bottom, and each is raised to the power 1, which is not written but understood:

$$K = \frac{[HI]^2}{[H_2][I_2]}$$

b. The product is SO_3, and the power is 2. The reactants are SO_2 (power = 2) and O_2 (power = 1).

$$K = \frac{[SO_3]^2}{[SO_2]^2[O_2]}$$

✔ **LEARNING CHECK 8.2** Write equilibrium expressions for the reactions represented by the following equations:

a. $N_2O_4(g) \rightleftarrows 2NO_2(g)$
b. $3NO(g) \rightleftarrows N_2O(g) + NO_2(g)$

For a reaction with an equilibrium position far to the right, the product concentrations [*W*] and [*X*] will be much higher than the reactant concentrations [*A*] and [*B*]. According to Equation 8.14, such a situation should result in a large *K* value. For reactions with equilibrium positions far to the left, a similar line of reasoning leads to the conclusion that *K* values should be small. Thus, the value of the equilibrium constant gives an indication of the position of equilibrium for a reaction.

Example 8.3 Calculating Equilibrium Constants

For each of the following equations, the equilibrium molarity concentration is given below each reactant and product. Calculate *K* for each reaction and comment on the position of equilibrium.

a.
$$\underset{8.23 \times 10^{-3}\ \mathrm{M}}{2NO_2(g)} \rightleftarrows \underset{1.46 \times 10^{-2}\ \mathrm{M\ at\ 25°C}}{N_2O_4(g)}$$

b.
$$\underset{0.200\ \mathrm{M}}{CH_4(g)} + \underset{0.150\ \mathrm{M}}{H_2O(g)} \rightleftarrows \underset{1.37 \times 10^{-2}\ \mathrm{M}}{CO(g)} + \underset{4.11 \times 10^{-2}\ \mathrm{M\ at\ 900\ K}}{3H_2(g)}$$

Solution a.

STEP 1: Examine the question for what is given and what is unknown.

Given: the balanced reaction
Unknown: $K = ?$
$[NO_2] = 8.23 \times 10^{-3}$ M
$[N_2O_4] = 1.46 \times 10^{-2}$ M

STEP 2: Identify a formula that links the given and unknown terms.

$$\text{Equation 8.14: } K = \frac{[W]^w[X]^x}{[A]^a[B]^b}$$

STEP 3: Enter the data into the formula.

$$K = \frac{[N_2O_4]}{[NO_2]^2} = \frac{(1.46 \times 10^{-2}\ \text{mol/L})}{(8.23 \times 10^{-3}\ \text{mol/L})^2} = \frac{2.16 \times 10^2}{\text{mol/L}}$$

We see that K is fairly large, which tells us that the equilibrium position is toward the right, or product, side of the reaction. The peculiar sounding "per mole per liter" unit is the result of the way concentration terms are arranged in the equilibrium expression. The unit will not be the same for the K in all reactions. These units are not ordinarily shown, a practice we will follow for the remainder of this chapter.

STEP 4: Check to see whether the answer makes sense.

Yes. The answer has the correct units and the correct number of significant figures, and the value seems reasonable.

Solution b.

STEP 1: Examine the question for what is given and what is unknown.

Given: the balanced reaction
Unknown: $K = ?$
$[CH_4] = 0.200\ \text{M}$
$[H_2O] = 0.150\ \text{M}$
$[CO] = 1.37 \times 10^{-2}\ \text{M}$
$[H_2] = 4.11 \times 10^{-2}\ \text{M}$

STEP 2: Identify a formula that links the given and unknown terms.

$$\text{Equation 8.14: } K = \frac{[W]^w[X]^x}{[A]^a[B]^b}$$

STEP 3: Enter the data into the formula.

$$K = \frac{[CO][H_2]^3}{[CH_4][H_2O]} = \frac{(1.37 \times 10^{-2}\ \text{mol/L})(4.11 \times 10^{-2}\ \text{mol/L})^3}{(0.200\ \text{mol/L})(0.150\ \text{mol/L})} = 3.17 \times 10^{-5}$$

The small value of K indicates that the equilibrium position is toward the left.

STEP 4: Check to see whether the answer makes sense.

Yes. The answer has the correct units and the correct number of significant figures, and the value seems reasonable.

✔ **LEARNING CHECK 8.3** The molar concentrations are given below the reactants and products in the equations for the following reactions. Calculate K and comment on the position of each equilibrium.

a. $Br_2(g) + I_2(g) \rightleftarrows 2IBr(g)$
$1.50 \times 10^{-1}\ \text{M}$ $\quad 5.00 \times 10^{-2}\ \text{M}$ $\quad 1.96 \times 10^{-2}\ \text{M}$ at 25°C

b. $N_2(g) + 3H_2(g) \rightleftarrows 2NH_3(g)$
$9.23 \times 10^{-3}\ \text{M}$ $\quad 2.77 \times 10^{-2}\ \text{M}$ $\quad 9.00\ \text{M}$ at 25°C

Example 8.3 illustrates that equilibrium constants for different reactions may be small or large. In fact, the two reactions used are by no means even close to the extremes encountered for K values. Some are so small (such as 1.1×10^{-36}) that for all practical purposes no products are present at equilibrium. Others are so large (such as 1.2×10^{40}) that the reaction can be considered to go completely to products. For reactions with K values between 10^{-3} and 10^3, the position of equilibrium is not extremely favorable to either side, and significant concentrations of both reactants and products can be detected in the equilibrium mixtures.

You might also have noticed in Example 8.3 that the equilibrium concentrations were given for specific temperatures. The reason for this is that *K* values are constant for a reaction as long as the temperature remains constant. However, *K* values will change as the temperature is changed. This is a demonstration of the effect of temperature on the position of equilibrium described in the next section.

8.8 Factors That Influence Equilibrium Position

Learning Objective 8 Use Le Châtelier's principle to predict the influence of changes in concentration and reaction temperature on the position of equilibrium for reactions.

Le Châtelier's principle The position of an equilibrium shifts in response to changes made in factors of the equilibrium.

A number of factors can change the position of an established equilibrium. The influence of such factors can be predicted by using a concept known as Le Châtelier's principle, in honor of its originator. According to **Le Châtelier's principle**, when a change is made in any factor of an established equilibrium, the position of equilibrium will shift in a direction that will minimize or oppose the change. The factors we will be most concerned with are concentrations of reactants and products, and reaction temperature.

The effect of concentration changes can be illustrated by the reaction of H_2 with I_2 (Equation 8.12):

$$H_2(g) + I_2(g) \rightleftarrows 2HI(g) \qquad (8.12)$$

Suppose an equilibrium mixture of H_2, I_2, and HI is formed. According to the molecular collision concept, favorable collisions are occurring between H_2 and I_2 molecules to form HI molecules, and favorable collisions are also taking place between HI molecules that cause them to form H_2 and I_2 molecules. Now, suppose some additional I_2 is added to the equilibrium mixture. The chances for favorable collisions between H_2 and I_2 molecules are increased; the rate of formation of HI is increased, and more HI is formed than disappears. The rate of reaction of HI to give H_2 and I_2 increases as the concentration of HI increases, and eventually a new equilibrium position and a new set of equilibrium concentrations will be established. The new equilibrium mixture will contain more HI than the original mixture, but the amounts of the reactants will also be different such that the equilibrium constant remains unchanged. The original equilibrium of the reaction has been shifted toward the right.

Le Châtelier's principle can also be used to predict the influence of temperature on an equilibrium by treating heat as a product or reactant. Consider the following equation for a hypothetical exothermic reaction:

$$A + B \rightleftarrows \text{products} + \text{heat} \qquad (8.15)$$

If the temperature is increased (by adding more heat, which appears on the right side of the equation), the equilibrium shifts to the left in an attempt to use up the added heat. In the new equilibrium position, the concentrations of *A* and *B* will be higher, whereas the chemical product concentrations will be lower than those in the original equilibrium. In this case the value of the equilibrium constant is changed by the change in temperature (see **Figure 8.16**).

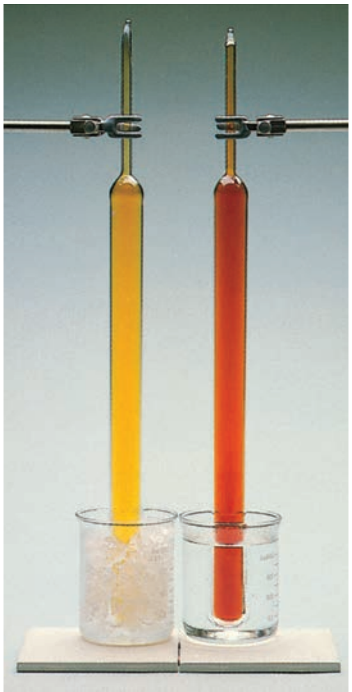

Michael C. Slabaugh

FIGURE 8.16 The effect of temperature on the position of equilibrium for the reaction $N_2O_4 \rightleftarrows 2NO_2$. *Left:* A sealed tube containing an equilibrium mixture of red-brown NO_2 and colorless N_2O_4 is cooled in an ice bath. *Right:* The same sealed tube is heated in a hot water bath. On which side of the equation will heat appear? Is the reaction exothermic or endothermic?

Example 8.4 Using Le Châtelier's Principle

The large-scale production of ammonia is important in meeting the agricultural demand for nitrogen-based fertilizers. Ammonia promotes plant growth and improves fruit and seed production.

Using Le Châtelier's principle, answer the following questions:

a. Ammonia is made from hydrogen and atmospheric nitrogen:

$$N_2(g) + 3H_2(g) \rightleftarrows 2NH_3(g) + \text{heat}$$

What effect will cooling have on an equilibrium mixture?

b. What effect will removing H_2 have on the equilibrium mixture described in part a?

c. Consider the following equation for a reaction that takes place in solution:

$$\underset{\substack{\text{light}\\\text{brown}}}{Fe^{3+}(aq)} + \underset{\text{colorless}}{6SCN^-(aq)} \rightleftarrows \underset{\text{dark red}}{Fe(SCN)_6{}^{3-}(aq)}$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

What effect will the addition of colorless NaSCN solid have on the color of the solution?

Solution

a. Heat is removed by cooling. Heat is replenished when the equilibrium shifts to the right. Thus, more NH_3 will be present at equilibrium in the cooler mixture.
b. The equilibrium will shift to the left in an attempt to replenish the H_2. At the new equilibrium position, less NH_3 will be present.
c. When solid NaSCN is added, it will dissolve and form ions:

$$NaSCN(s) \longrightarrow Na^{+}(aq) + SCN^{-}(aq)$$

The SCN^- concentration in the solution will therefore be increased. In an attempt to use up the added SCN^-, the equilibrium will shift to the right. This shift generates more of the dark red $Fe(SCN)_6^{3-}$. Therefore, the new position of equilibrium will be characterized by a darker red color.

✔ LEARNING CHECK 8.4 Use Le Châtelier's principle and answer the following:

a. A saturated solution of ammonium nitrate is formed as follows. The solution process is endothermic:

$$heat + NH_4NO_3(s) \rightleftarrows NH_4^{+}(aq) + NO_3^{-}(aq)$$

Which way will the equilibrium shift when heat is added? What does this shift mean in terms of the solubility of NH_4NO_3 at the higher temperature?

b. Sulfur trioxide gas is formed when oxygen and sulfur dioxide gas react:

$$2SO_2(g) + O_2(g) \rightleftarrows 2SO_3(g)$$

Which way would the equilibrium shift if O_2 were removed from the system? How would the new equilibrium concentration of SO_3 compare with the earlier equilibrium concentration?

Catalysts cannot change the position of an equilibrium. This fact becomes clear when you remember that a catalyst functions by lowering the activation energy for a reaction. A lowering of the energy barrier for the forward reaction also lowers the barrier for the reverse reaction (see **Figure 8.17**). Hence, a catalyst speeds up both the forward and reverse reactions and cannot change the position of equilibrium. However, the lowered activation energy allows equilibrium to be established more quickly than if the catalyst were absent.

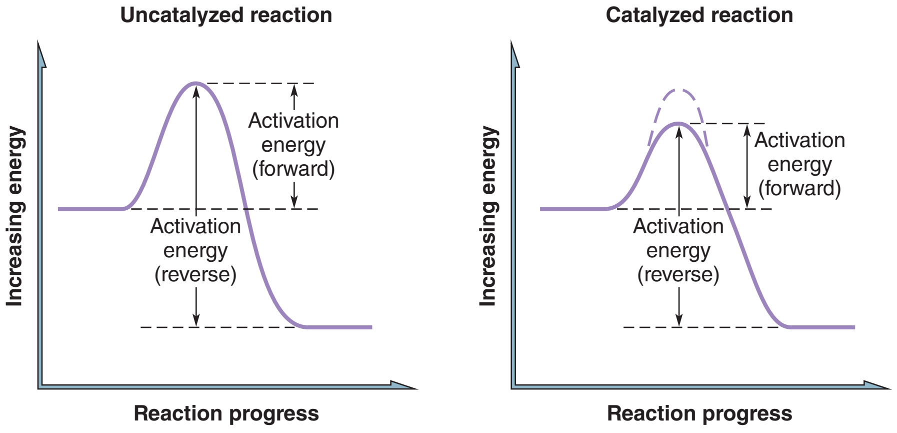

Uncatalyzed reaction
Catalyzed reaction
Increasing energy
Activation energy (forward)
Activation energy (reverse)
Reaction progress
Increasing energy
Activation energy (forward)
Activation energy (reverse)
Reaction progress

FIGURE 8.17 The influence of catalysts on forward and reverse activation energies.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STUDY TOOLS 8.1

Le Châtelier's Principle in Everyday Life

Le Châtelier's principle is extremely important in laboratory work and in the chemical industry when the goal is to obtain the maximum amount of product from a reaction. In such cases, increasing reactant concentrations, or adjusting the reaction temperature or pressure to shift the equilibrium position to the product side of the reaction, is a common practice.

To help you understand Le Châtelier's principle, it is often useful to observe familiar situations and events and interpret them in terms of shifting equilibria. For example, when you stand in an upright position, you are in equilibrium with the force of gravity. If a friend leans against you, your equilibrium is upset, and you will lose your balance unless you respond by leaning toward your friend such that the forces on you are once again balanced.

Children playing on a seesaw provide a similar example of forces in equilibrium. If one child slides toward the center of the seesaw, the force acting on that side is reduced, the equilibrium is upset, and the other child will be firmly on the ground. However, if the second child also shifts toward the center, the forces on each side can be made equal again, and play can resume.

The preceding examples involved equilibrium between forces, but we are not limited to only those types of examples. Imagine you are enjoying a warm shower when someone turns on a nearby hot water faucet. Suddenly, your shower turns cold. You respond to this stress by adjusting the shower controls (after shrieking loudly) to let in more hot water in an attempt to restore the pleasant temperature you were enjoying. (However, be aware of what will happen when the other faucet is turned off.)

Be mindful of your surroundings and activities, and you will see many more examples that will remind you of responses to stress that are attempts to restore equilibrium to a previous situation.

Health Career Description

PHYSICIAN'S ASSISTANT

As the name implies, Physician Assistants (PAs) "assist physicians." Their role varies by which type of physician they assist. They may work with allergists, surgeons, ob-gyn physicians, general practice physicians, or any other type of physician. PAs work in collaboration with a physician, but they enjoy a high level of autonomy. While working under the guidance and supervision of a physician, PAs maintain the ability to see patients one-on-one and to prescribe medications.

In order to become a PA, individuals must first earn a bachelor's degree and accumulate patient-contact hours. Although they may major in any subject, the most straightforward path is to major in one of the "life sciences," such as biochemistry, microbiology, biology, or zoology, because the required prerequisite coursework will count toward the requirements for these majors.

According to the University of Utah School of Medicine PA program requirements, a successful applicant will have the following items included on their transcript:

- Bachelor's degree from a regionally accredited institution
- Anatomy with lab (4 credits)
- Physiology with lab (4 credits)
- Biology (4 credits)
- Chemistry (8 credits —lab credit may be included)
- Other recommended coursework:
  - Writing
  - Diversity and cultural awareness courses
  - Genetics
  - Statistics

PA applicants apply through an online service called CASPA (Centralized Application Service for Physician Assistants). Along with proof of patient-contact hours, applicants must submit a 5000-word essay explaining why they want to become a PA. The essay is an important piece of the application. It is your chance to stand out from the crowd.

After successful completion of a PA program, graduates must pass the PANCE (the Physician Assistant National Certifying Exam). This is the final hurdle in becoming a PA. Although it is common to take much longer, it's possible to complete requirements for PA certification within 6 years after beginning a bachelor's program.

Because medical school is long, expensive, and competitive, there are not enough medical doctors to keep up with the growing need for medical care. PAs fill an important need within the health care system.

Concept Summary

8.1 Spontaneous and Nonspontaneous Processes

Learning Objective: Can you use the concepts of energy and entropy to predict the spontaneity of processes and reactions?

- Spontaneous processes take place naturally, with no apparent cause or stimulus.
- Process spontaneity depends on the energy and entropy changes that accompany the process.
- Energy decreases and entropy increases favor spontaneity.
- However, a nonspontaneous change in one of these factors can be compensated for by a large spontaneous change in the other to cause processes to be spontaneous.

8.2 Reaction Rates

Learning Objective: Can you calculate reaction rates from experimental data?

- The speed of a reaction is called a reaction rate.
- Reaction rate can be determined by measuring how fast reactants are consumed or products are formed.

8.3 Molecular Collisions

Learning Objective: Can you use the concept of molecular collisions to explain reaction characteristics?

- Explanations of how reactions take place are called reaction mechanisms.
- Most mechanisms are based on three assumptions.
  - Molecules must collide with one another.
  - The collision must involve a certain minimum of energy.
  - Some colliding molecules must be oriented in a specific way during collision in order to react.

8.4 Energy Diagrams

Learning Objective: Can you represent and interpret the energy relationships for reactions by using energy diagrams?

- Energy relationships for reactions can be represented by energy diagrams, in which energy is plotted versus the reaction progress.
- The concepts of exothermic and endothermic reactions and activation energy are clearly represented by such diagrams.

8.5 Factors That Influence Reaction Rates

Learning Objective: Can you explain how factors such as reactant concentrations, temperature, and catalysts influence reaction rates?

- Four factors affect the rates of all reactions.
  - The nature of the reactants
  - Reactant concentrations
  - Reactant temperature
  - The presence of catalysts

8.6 Chemical Equilibrium

Learning Objective: Can you relate experimental observations to the establishment of equilibrium?

- Reactions are in equilibrium when the rate of the forward reaction is equal to the rate of the reverse reaction.
- Equilibrium is emphasized in equations for reactions by writing double arrows pointing in both directions between reactants and products.

8.7 The Position of Equilibrium

Learning Objective: Can you write equilibrium expressions based on reaction equations, and do calculations based on equilibrium expressions?

- The relative amounts of reactants and products present in a system at equilibrium define the position of equilibrium.
- The equilibrium position is toward the right when a large amount of product is present and toward the left when a large amount of reactant is present.
- The position is indicated by the value of the equilibrium constant.

8.8 Factors That Influence Equilibrium Position

Learning Objective: Can you use Le Châtelier's principle to predict the influence of changes in concentration and reaction temperature on the position of equilibrium for reactions?

- Factors known to influence the position of equilibrium includes changes in amount of reactants and/or products and changes in temperature.
- The influence of such factors can be predicted by using Le Châtelier's principle.
- Catalysts cannot change the position of equilibrium.

Key Terms and Concepts

Activation energy (8.3)
Catalyst (8.5)
Effective collision (8.5)
Endergonic process (8.1)
Entropy (8.1)
Equilibrium concentrations (8.6)
Equilibrium constant (8.7)
Equilibrium expression (8.7)
Exergonic process (8.1)
Heterogeneous (surface) catalyst (8.5)
Homogeneous catalyst (8.5)
Inhibitor (8.5)
Internal energy (8.3)
Le Châtelier's principle (8.8)
Position of equilibrium (8.7)
Reaction mechanism (8.3)
Reaction rate (8.2)
Spontaneous process (8.1)
Stable substance (8.1)
State of equilibrium (8.6)

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Key Equations

1. Calculation of reaction rate (**Section 8.2**):	$\text{Rate} = \frac{\Delta C}{\Delta t} = \frac{C_t - C_0}{\Delta t}$	Equation 8.1
2. Equilibrium expression for general reaction (**Section 8.7**):	$aA + bB + \cdots \rightleftarrows wW + xX + \cdots$ $K = \frac{[W]^w[X]^x}{[A]^a[B]^b}$	Equation 8.13 Equation 8.14

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Spontaneous and Nonspontaneous Processes (Section 8.1)

8.1 Classify the following processes as spontaneous or nonspontaneous. Explain your answers in terms of whether energy must be continually supplied to keep the process going.

- **a.** Water is decomposed into hydrogen and oxygen gas by passing electricity through the liquid.
- **b.** An explosive detonates after being struck by a falling rock.
- **c.** A coating of magnesium oxide forms on a clean piece of magnesium exposed to air.
- **d.** A light bulb emits light when an electric current is passed through it.
- **e.** A cube of sugar dissolves in a cup of hot coffee.

8.2 Classify the following processes as spontaneous or nonspontaneous. Explain your answers in terms of whether energy must be continually supplied to keep the process going.

- **a.** The space shuttle leaves its pad and goes into orbit.
- **b.** The fuel in a booster rocket of the space shuttle burns.
- **c.** Water boils at 100°C and 1 atm pressure.
- **d.** Water temperature increases to 100°C at 1 atm pressure.
- **e.** Your bedroom becomes orderly.

8.3 Classify the following processes as exergonic or endergonic. Explain your answers.

- **a.** Any combustion process
- **b.** Perspiration evaporating from the skin
- **c.** Melted lead solidifying
- **d.** An explosive detonating
- **e.** An automobile being pushed up a slight hill (from point of view of the automobile)

8.4 Classify the following processes as exergonic or endergonic. Explain your answers.

- **a.** An automobile being pushed up a slight hill (from point of view of the one pushing)
- **b.** Ice melting (from point of view of the ice)
- **c.** Ice melting (from point of view of surroundings of the ice)
- **d.** Steam condensing to liquid water (from point of view of the steam)
- **e.** Steam condensing to liquid water (from point of view of surroundings of the steam)

8.5 Describe the energy and entropy changes that occur in the following processes, and indicate whether the processes are spontaneous under the conditions stated:

- **a.** Lumber becomes a house.
- **b.** Books are shelved in a library.
- **c.** On a hot day, water evaporates from a lake.

8.6 Describe the energy and entropy changes that occur in the following processes, and indicate whether the processes are spontaneous under the conditions stated:

- **a.** On a cold day, water freezes.
- **b.** A container of water at 40°C cools to room temperature.
- **c.** The odor from an open bottle of perfume spreads throughout a room.

8.7 Pick the example with the highest entropy from each of the following sets. Explain your answers.

- **a.** Solid ice, liquid water, or steam
- **b.** Leaves on a tree, fallen leaves blown about on the ground, fallen leaves raked and placed in a basket
- **c.** A stack of sheets of paper, a wastebasket containing sheets of paper, a wastebasket containing torn and crumpled sheets of paper
- **d.** A 0.10 M sugar solution, a 1.0 M sugar solution, a 10.0 M sugar solution
- **e.** A banquet table set for dinner, a banquet table during dinner, a banquet table immediately after dinner

8.8 Pick the example with the highest entropy from each of the following sets. Explain your answers.

- **a.** Two opposing football teams just before the ball is snapped, two opposing football teams 1 second after the ball is snapped, two opposing football teams when the whistle is blown, ending the play
- **b.** A 10% copper/gold alloy, a 2% copper/gold alloy, pure gold

c. A purse on which the strap just broke, a purse just hitting the ground, a purse on the ground with contents scattered

d. Coins in a piggy bank, coins in piles containing the same type of coins, coins in stacks of the same type of coins

e. A dozen loose pearls in a box, a dozen pearls randomly strung on a string, a dozen pearls strung on a string in order of decreasing size

8.9 You probably know that on exposure to air silver tarnishes and iron rusts; but gold, stainless steel, and chromium do not change. Explain these facts, using the concept of stability.

Reaction Rates (Section 8.2)

8.10 Classify the following processes according to their rates as very slow, slow, or fast:

a. The souring of milk stored in a refrigerator

b. The cooking of an egg in boiling water

c. The rusting of a shovel left in the garden over the winter

d. The growing of corn during a warm summer

e. The burning of a lighted match.

8.11 Classify the following processes according to their rates as very slow, slow, or fast:

a. The melting of butter put into a hot pan

b. The ripening of a piece of fruit stored at room temperature

c. The cooking of a raw potato in a hot oven

d. The melting of an ice cube in a glass of cool water

e. The combustion of gasoline in the engine of a car

8.12 Describe the observations or measurements that could be made to allow you to follow the rate of the following processes:

a. The melting of a block of ice

b. The setting (hardening) of concrete

c. The burning of a candle

8.13 Describe the observations or measurements that could be made to allow you to follow the rate of the following processes:

a. The diffusion of ink from a drop placed in a pan of quiet, undisturbed water

b. The loss of water from a pan of boiling water

c. The growth of a corn plant

8.14 Consider the following hypothetical reaction:

$$A + B \rightarrow C$$

Calculate the average rate of the reaction on the basis of the following information:

a. Pure A and B are mixed, and after 12.0 minutes the measured concentration of C is 0.396 mol/L.

b. Pure A, B, and C are mixed together at equal concentrations of 0.300 M. After 8.00 minutes, the concentration of C is found to be 0.455 M.

8.15 Consider the following hypothetical reaction:

$$A + B \rightarrow C$$

Calculate the average rate of the reaction on the basis of the following information:

a. Pure A, B, and C are mixed together at concentrations of $A + B = 0.400$ M, $C = 0.150$ M. After 6.00 minutes, the concentration of C is 0.418 M.

b. Pure A and B are mixed together at the same concentration of 0.361 M. After 7.00 minutes, the concentration of A is found to be 0.048 M.

8.16 A reaction generates chlorine gas (Cl_2) as a product. The reactants are mixed and sealed in a 250.0-mL container. After 30.0 minutes, 2.97×10^{-2} mol of Cl_2 has been generated. Calculate the average rate of the reaction.

8.17 A reaction generates hydrogen gas (H_2) as a product. The reactants are mixed and sealed in a 250.0-mL vessel. After 20.0 minutes, 3.91×10^{-2} mol H_2 has been generated. Calculate the average rate of the reaction.

8.18* Ammonium and nitrite ions react in solution to form nitrogen gas:

$$NH_4^+\ (aq) + NO_2^-\ (aq) \rightarrow N_2(g) + 2H_2O(\ell)$$

A reaction is run, and the liberated N_2 gas is collected in a previously evacuated 500.0-mL container. After the reaction has gone on for 750.0 seconds, the pressure of N_2 in the 500.-mL container is 2.77×10^{-2} atm, and the temperature of the N_2 is 25.0°C. Use the ideal gas law (Equation 6.9) to calculate the number of moles of N_2 liberated. Then calculate the average rate of the reaction.

8.19* Suppose a small lake is contaminated with an insecticide that decomposes with time. An analysis done in June shows the decomposition product concentration to be 7.8×10^{-4} mol/L. An analysis done 35 days later shows the concentration of decomposition product to be 9.9×10^{-4} mol/L. Assume the lake volume remains constant and calculate the average rate of decomposition of the insecticide.

Molecular Collisions (Section 8.3)

8.20 In each of the following, which reaction mechanism assumption is apparently being violated? Explain your answers.

a. A reaction takes place more rapidly when the concentration of reactants is decreased.

b. A reaction takes place more rapidly when the reaction mixture is cooled.

c. The reaction rate of $A + B \rightarrow A{-}B$ increases as the concentration of A is increased but does not change as the concentration of B is increased.

8.21 Which reaction mechanism assumptions are unimportant in describing simple ionic reactions between cations and anions? Why?

8.22 Describe two ways by which an increase in temperature increases a reaction rate.

Energy Diagrams (Section 8.4)

8.23 Sketch energy diagrams to represent each of the following. Label the diagrams completely and tell how they are similar to each other and how they are different.

a. Exothermic (exergonic) reaction with activation energy

b. Exothermic (exergonic) reaction without activation energy

8.24 Sketch energy diagrams to represent each of the following. Label the diagrams completely and tell how they are similar to each other and how they are different.

a. Endothermic (endergonic) reaction with activation energy

b. Endothermic (endergonic) reaction without activation energy

8.25 Use energy diagrams to compare catalyzed and uncatalyzed reactions.

8.26 One reaction occurs at room temperature and liberates 500 kJ/mol of reactant. Another reaction does not take place until the reaction mixture is heated to 150°C. However, it also liberates 500 kJ/mol of reactant. Draw an energy diagram for each reaction and indicate the similarities and differences between the two.

Factors That Influence Reaction Rates (Section 8.5)

8.27 The following reactions are proposed. Make a rough estimate of the rate of each one—rapid, slow, won't react. Explain each answer.

a. $H_2O(\ell) + H^+(aq) \rightarrow H_3O^+(aq)$

b. $H_3O^+(aq) + H^+(aq) \rightarrow H_4O^{2+}(aq)$

c. $3H_2(g) + N_2(g) \rightarrow 2NH_3(g)$

d. $Ba^{2+}(aq) + SO_4{}^{2-}(aq) \rightarrow BaSO_4(s)$

8.28 The following reactions are proposed. Make a rough estimate of the rate of each one—rapid, slow, won't react. Explain each answer.

a. $CaO(s) + 2HCl(g) \rightarrow CaCl_2(s) + H_2O(\ell)$

b. $2KI(s) + Pb(NO_3)_2(s) \rightarrow PbI_2(s) + 2KNO_3(s)$

c. $Cl^-(aq) + I^-(aq) \rightarrow ICl^{2-}(aq)$

d. $I_2(aq) + I^-(aq) \rightarrow I_3{}^-(aq)$

8.29 Which reaction mechanism assumption is most important in explaining the following? Why?

a. The influence of concentration on reaction rates

b. The influence of catalysts on reaction rates

8.30 Suppose you are running a reaction and you want to speed it up. Describe three things you might try to do this.

8.31 A reaction is started by mixing reactants. As time passes, the rate decreases. Explain this behavior that is characteristic of most reactions.

8.32 A reaction is run at 10°C and takes 3.7 hours to go to completion. How long would it take to complete the reaction at 30°C?

8.33 What factor is more important than simply the amount of solid reactant present in determining the rate of a reaction? Explain.

8.34 Describe two ways catalysts might speed up a reaction.

Chemical Equilibrium (Section 8.6)

8.35 Describe the establishment of equilibrium in a system represented by a shopper walking up the "down" escalator.

8.36 Describe the observation or measurement result that would indicate when each of the following had reached equilibrium:

a.

H_2	+	I_2	$\rightleftarrows$	2HI
colorless gas		violet gas		colorless gas

b. solid sugar + water $\rightleftarrows$ sugar solution

c.

N_2	+	$2O_2$	$\rightleftarrows$	$2NO_2$
colorless gas		colorless gas		red-brown gas

8.37 Describe the observation or measurement result that would indicate when each of the following had reached equilibrium:

a.

2CO	+	O_2	$\rightleftarrows$	$2CO_2$
colorless gas		colorless gas		colorless gas (apply Dalton's law)

b.

LiOH	+	CO_2	$\rightleftarrows$	$LiHCO_3$
colorless solid		colorless gas		colorless solid

c. paycheck → checking account → checks to pay bills

8.38 Colorless hydrogen gas (H_2) and red-brown colored bromine gas (Br_2) react to form colorless HBr gas. Describe how the concentrations of H_2, Br_2, and HBr would change (increase or decrease) as equilibrium was established in a sealed container that initially contained only H_2 and Br_2. What observation would indicate that equilibrium had been established?

8.39 Colorless N_2O_4 gas decomposes to form red-brown colored NO_2 gas. Describe how the concentrations of N_2O_4 and NO_2 would change (increase or decrease) as equilibrium was established in a sealed container that initially contained only N_2O_4. What observation would indicate that equilibrium had been established?

The Position of Equilibrium (Section 8.7)

8.40 Write an equilibrium expression for each of the following gaseous reactions:

a. $2CO + O_2 \rightleftarrows 2CO_2$

b. $N_2O_4 \rightleftarrows 2NO_2$

c. $2C_2H_6 + 7O_2 \rightleftarrows 4CO_2 + 6H_2O$

d. $2NOCl \rightleftarrows 2NO + C1_2$

e. $2Cl_2O_5 \rightleftarrows O_2 + 4C1O_2$

8.41 Write an equilibrium expression for each of the following gaseous reactions:

a. $3O_2 \rightleftarrows 2O_3$

b. $COCl_2 \rightleftarrows CO + Cl_2$

c. $CS_2 + 4H_2 \rightleftarrows CH_4 + 2H_2S$

d. $2SO_2 + O_2 \rightleftarrows 2SO_3$

e. $CO + H_2O \rightleftarrows CO_2 + H_2$

8.42 The following equilibria are established in water solutions. Write an equilibrium expression for each reaction.

a. $Fe^{3+} + 6CN^- \rightleftarrows Fe(CN)_6{}^{3-}$

b. $Ag^+ + 2NH_3 \rightleftarrows Ag(NH_3)_2{}^+$

c. $Au^{3+} + 4Cl^- \rightleftarrows AuCl_4{}^-$

8.43 The following equilibria are established in water solutions. Write an equilibrium expression for each reaction.

a. $Ni^{2+} + 6NH_3 \rightleftarrows Ni(NH_3)_6{}^{2+}$

b. $Sn^{2+} + 2Fe^{3+} \rightleftarrows Sn^{4+} + 2Fe^{2+}$

c. $F_2 + 2Cl^- \rightleftarrows 2F^- + Cl_2$

8.44 Write a reaction equation that corresponds to each of the following equilibrium expressions:

a. $K = \dfrac{[CO_2][H_2O]^2}{[CH_4][O_2]^2}$

b. $K = \dfrac{[CH_4][H_2O]}{[H_2]^3[CO]}$

c. $K = \dfrac{[O_2]^3}{[O_3]^2}$

d. $K = \dfrac{[NH_3]^4[O_2]^7}{[NO_2]^4\,[H_2O]^6}$

8.45 Write a reaction equation that corresponds to each of the following equilibrium expressions:

a. $K = \dfrac{[PH_3][F_2]^3}{[HF]^3[PF_3]}$

b. $K = \dfrac{[O_2]^7[NH_3]^4}{[NO_2]^4[H_2O]^6}$

c. $K = \dfrac{[O_2][ClO_2]^4}{[Cl_2O_5]^2}$

d. $K = \dfrac{[N_2][H_2O]^2}{[NO]^2[H_2]^2}$

8.46 A sample of gaseous BrCl is allowed to decompose in a closed container at 25°C:

$$2BrCl(g) \rightleftarrows Br_2(g) + Cl_2(g)$$

When the reaction reaches equilibrium, the following concentrations are measured: $[BrCl] = 0.38$ M, $[Cl_2] = 0.26$ M, $[Br_2] = 0.26$ M. Evaluate the equilibrium constant for the reaction at 25°C.

8.47 At 600°C, gaseous CO and Cl_2 are mixed together in a closed container. At the instant they are mixed, their concentrations are CO = 0.79 mol/L and Cl_2 = 0.69 mol/L. After equilibrium is established, their concentrations are CO = 0.25 mol/L and Cl_2 = 0.15 mol/L. Evaluate the equilibrium constant for the reaction

$$CO(g) + Cl_2(g) \rightleftarrows COCl_2(g)$$

8.48 A mixture of the gases NOCl, Cl_2, and NO is allowed to reach equilibrium at 25°C. The measured equilibrium concentrations are [NO] = 0.92 mol/L, [NOCl] = 1.31 mol/L, and $[Cl_2]$ = 0.20 mol/L. What is the value of the equilibrium constant at 25°C for the reaction

$$2NOCl(g) \rightleftarrows 2NO(g) + Cl_2(g)$$

8.49 Consider the following equilibrium constants. Describe how you would expect the equilibrium concentrations of reactants and products to compare with each other (larger than, smaller than, etc.) for each case.

a. $K = 2.1 \times 10^{-6}$

b. $K = 0.15$

c. $K = 1.2 \times 10^{8}$

d. $K = 0.00036$

8.50 Consider the following equilibrium constants. Describe how you would expect the equilibrium concentrations of reactants and products to compare with each other (larger than, smaller than, etc.) for each case.

a. $K = 5.9$

b. $K = 3.3 \times 10^{6}$

c. $K = 2.7 \times 10^{-4}$

d. $K = 0.0000558$

Factors That Influence Equilibrium Position (Section 8.8)

8.51 Use Le Châtelier's principle to predict the direction of equilibrium shift in the following equilibria when the indicated stress is applied:

a. $2A + B + \text{heat} \rightleftarrows C$; some A is removed.

b. $2A + B + \text{heat} \rightleftarrows C + D$; the system is cooled.

c. $N_2O_4 \rightleftarrows 2NO_2$; some NO_2 is removed.

8.52 Use Le Châtelier's principle to predict the direction of equilibrium shift in the following equilibria when the indicated stress is applied:

a. $Ag^+(aq) + Cl^-(aq) \rightleftarrows AgCl(s)$; some Ag^+ is removed.

b. $2HI(g) + \text{heat} \rightleftarrows H_2(g) + I_2(g)$; the system is heated.

c. $6Cu(s) + N_2(g) + \text{heat} \rightleftarrows 2Cu_3N(s)$; the system is cooled and some N_2 is removed.

8.53 Use Le Châtelier's principle to predict the direction of equilibrium shift and the changes that will be observed (color, amount of precipitate, etc.) in the following equilibria when the indicated stress is applied:

a. $\text{heat} + Co^{2+}(aq) + 4Cl^-(aq) \rightleftarrows CoCl_4{}^{2-}(aq)$;
pink colorless blue
The equilibrium mixture is heated.

b. $\text{heat} + Co^{2+}(aq) + 4Cl^-(aq) \rightleftarrows CoCl_4{}^{2-}(aq)$;
pink colorless blue
Co^{2+} is added to the equilibrium mixture.

c. $Fe^{3+}(aq) + 6SCN^-(aq) \rightleftarrows Fe(SCN)_6{}^{3-}(aq)$;
brown colorless red
SCN^- is added to the equilibrium mixture.

d. $Pb^{2+}(aq) + 2Cl^-(aq) \rightleftarrows PbCl_2(s) + \text{heat}$;
colorless colorless white solid
Pb^{2+} is added to the equilibrium mixture.

e. $C_2H_4 + I_2 \rightleftarrows C_2H_4I_2 + \text{heat}$;
colorless gas violet gas colorless gas
A catalyst is added to the equilibrium mixture.

8.54 Use Le Châtelier's principle to predict the direction of equilibrium shift and the changes that will be observed (color, amount of precipitate, etc.) in the following equilibria when the indicated stress is applied:

a. $Cu^{2+}(aq) + 4NH_3(aq) \rightleftarrows Cu(NH_3)_4{}^{2+}(aq)$;
blue colorless dark purple
Some NH_3 is added to the equilibrium mixture.

b. $Pb^{2+}(aq) + 2Cl^-(aq) \rightleftarrows PbCl_2(s) + \text{heat}$;
colorless colorless white solid
The equilibrium mixture is cooled.

c. $C_2H_4 + I_2 \rightleftarrows C_2H_4I_2 + \text{heat}$;
colorless gas violet gas colorless gas
Some $C_2H_4I_2$ is removed from the equilibrium mixture.

d. $\underset{\text{colorless gas}}{C_2H_4} + \underset{\text{violet gas}}{I_2} \rightleftarrows \underset{\text{colorless gas}}{C_2H_4I_2} + \text{heat};$
The equilibrium mixture is cooled.

e. $\text{heat} + \underset{\text{brown gas}}{4NO_2} + \underset{\text{colorless gas}}{6H_2O} \rightleftarrows \underset{\text{colorless gas}}{7O_2} + \underset{\text{colorless gas}}{4NH_3};$
A catalyst is added, and NH_3 is added to the equilibrium mixture.

8.55* Tell what will happen to each equilibrium concentration in the following when the indicated stress is applied and a new equilibrium position is established:

a. $H^+(aq) + HCO_3^-(aq) \rightleftarrows H_2O(\ell) + CO_2(g)$;
HCO_3^- is added.

b. $CO_2(g) + H_2O(\ell) \rightleftarrows H_2CO_3(aq) + \text{heat}$;
CO_2 is removed.

c. $CO_2(g) + H_2O(\ell) \rightleftarrows H_2CO_3(aq) + \text{heat}$;
The system is cooled.

8.56* Tell what will happen to each equilibrium concentration in the following when the indicated stress is applied and a new equilibrium position is established:

a. $LiOH(s) + CO_2(g) \rightleftarrows LiHCO_3(s) + \text{heat}$; CO_2 is removed.

b. $2NaHCO_3(s) + \text{heat} \rightleftarrows Na_2O(s) + 2CO_2(g) + H_2O(g)$;
The system is cooled.

c. $CaCO_3(s) + \text{heat} \rightleftarrows CaO(s) + CO_2(g)$; The system is cooled.

8.57 The gaseous reaction $2HBr(g) \rightleftarrows H_2(g) + Br_2(g)$ is endothermic. Tell which direction the equilibrium will shift for each of the following:

a. Some H_2 is added.

b. The temperature is increased.

c. Some Br_2 is removed.

d. A catalyst is added.

e. Some HBr is removed.

f. The temperature is decreased, and some HBr is removed.

8.58 The gaseous reaction $N_2(g) + 3H_2(g) \rightleftarrows 2NH_3(g)$ is exothermic. Tell which direction the equilibrium will shift for each of the following:

a. Some N_2 is added.

b. The temperature is increased.

c. Some NH_3 is removed.

d. Some H_2 is removed.

e. A catalyst is added.

f. The temperature is increased, and some H_2 is removed.

Additional Exercises

8.59 Assume the following reactions take place under identical conditions of concentration and temperature. Which reaction would you expect to take place faster? Explain your answer.

a. $H_2(g) + F_2(g) \rightarrow 2HF(g)$

b. $H_2(g) + I_2(g) \rightarrow 2HI(g)$

8.60 Gases A and B react as follows: $A(g) + B(g) \rightarrow C(s)$. Suppose gases A and B are mixed and used to fill a balloon. How could you increase the concentration of A and B, and speed up the reaction?

8.61 Bacteria found in lakes use dissolved oxygen gas to metabolize organic contaminants and use them as a food source, thus removing the contaminants from the lakes. When lake temperatures increase significantly, the rate of this chemical decontamination decreases. Remember your study of gases and explain this apparent violation of the factors influencing reaction rates studied in this chapter.

8.62 In **Section 8.1** of this chapter, three criteria that determine the spontaneity of a process are given. Review these criteria, and determine which one is involved in each of the following spontaneous phase changes:

a. Evaporation of a liquid

b. Condensation of a gas to a liquid

c. Sublimation of a solid to a gas

d. Liquefaction of a gas to a liquid

e. Crystallization of a liquid to a solid

Chemistry for Thought

8.63 Refer to **Figure 8.7** and answer the question. How would the total energy released as light for each light stick compare when they have both stopped glowing?

8.64 A mixture of the gases NOCl, NO, and Cl_2 is allowed to come to equilibrium at 400°C in a 1.50 L reaction container. Analysis shows the following number of moles of each substance to be present at equilibrium: NOCl = 1.80 mol, NO = 0.70 mol, and Cl_2 = 0.35 mol. Calculate the value of the equilibrium constant for the reaction at 400°C. The equation for the reaction is

$$2NOCl(g) \rightleftarrows 2NO(g) + Cl_2(g)$$

8.65 The equilibrium constant for the reaction $PCl_5 \rightleftarrows PCl_3 + Cl_2$ is 0.0245 at 250°C. What molar concentration of PCl_5 would be present at equilibrium if the concentrations of PCl_3 and Cl_2 were both 0.250 M?

8.66 At 448°C, the equilibrium constant for the reaction $H_2 + I_2 \rightleftarrows 2HI$ is 50.5. What concentration of I_2 would be found in an equilibrium mixture in which the concentrations of HI and H_2 were 0.500 M and 0.050 M, respectively?

8.67 Refer to **Figure 8.13** and answer the questions. Would you expect a crushed antacid tablet (like Alka-Seltzer) to dissolve faster or slower than a whole tablet? Explain.

8.68 Refer to **Figure 8.16** and answer the question. Would the presence of a catalyst in the tube influence the equilibrium concentrations of the two gases? Explain.

8.69 In the blood, both oxygen (O_2) and poisonous carbon monoxide (CO) can react with hemoglobin (Hb). The respective compounds are HbO_2 and HbCO. When both gases are present in the blood, the following equilibrium is established:

$$HbCO + O_2 \rightleftarrows HbO_2 + CO$$

Use Le Châtelier's principle to explain why pure oxygen is often administered to victims of CO poisoning.

8.70 Use the concept of reaction rates to explain why no smoking is allowed in hospital areas where patients are being administered oxygen gas.

8.71 Suppose you have two identical unopened bottles of carbonated beverage. The contents of both bottles appear to be perfectly clear. You loosen the cap of one of the bottles and hear a hiss as gas escapes, and at the same time gas bubbles appear in the liquid. The liquid in the unopened bottle still appears to be perfectly clear. Explain these observations using the concept of equilibrium and Le Châtelier's principle. Remember, a carbonated beverage contains carbon dioxide gas dissolved in a liquid under pressure.

8.72 Someone once suggested that it is impossible to unscramble a scrambled egg. Describe an unscrambled and a scrambled egg in terms of the concept of entropy.

9 Acids, Bases, and Salts

SDI Productions/E+/Getty Images

Health Career Focus

RESPIRATORY THERAPIST

Respiratory therapy is ranked among the most competitive programs at the university. My heart sank when I saw "alternate" on my notification of admission to the program—then, two days before the semester started, I received another letter informing me of an opening. What a surprise! It felt like such a roller-coaster in the beginning—but now, I work at a large community hospital.

The other night, while checking a patient on a ventilator, I noticed his hands and feet spasming. I recognized this sign of respiratory alkalosis and notified his nurse. When the order came to perform an arterial blood gas measurement, I recalled my nervousness in performing that test for the first time; now, I proudly conduct it with confidence. The test results showed a blood pH imbalance, with a pH greater than 7.5. I increased the breaths per minute setting on the ventilator to correct it.

How satisfying to know that my observations help to keep the patients safe!

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Write reaction equations that illustrate Arrhenius acid–base behavior. **(Section 9.1)**
2. Write reaction equations that illustrate Brønsted acid–base behavior, and identify Brønsted acids and bases from written reaction equations. **(Section 9.2)**
3. Name common acids. **(Section 9.3)**
4. Do calculations using the concept of the self-ionization of water. **(Section 9.4)**
5. Do calculations using the pH concept. **(Section 9.5)**
6. Write reaction equations that illustrate the characteristic reactions of acids. **(Section 9.6)**
7. Write reaction equations that represent neutralization reactions between acids and bases. **(Section 9.7)**
8. Write reaction equations that illustrate various ways to prepare salts, and do calculations using the concept of an equivalent of salt. **(Section 9.8)**
9. Demonstrate an understanding of the words *weak* and *strong* as applied to acids and bases. **(Section 9.9)**

10 Demonstrate an understanding of the titration technique used to analyze acids and bases. **(Section 9.10)**

11 Do calculations related to the analysis of acids and bases by titration. **(Section 9.11)**

12 Explain the concept of salt hydrolysis, and write equations to illustrate the concept. **(Section 9.12)**

13 Explain how buffers work, and write equations to illustrate their action. **(Section 9.13)**

ACIDS, BASES, AND SALTS are among the most common and important solutes found in solutions. Until late in the 19th century, these substances were characterized by properties, such as taste and color changes induced in certain dyes. Acids taste sour (see **Figure 9.1**); bases, bitter; and salts, salty. Litmus, a dye, is red in the presence of acids and blue in the presence of bases. These and other observations led to the correct conclusions that acids and bases are chemical opposites and that salts are produced when acids and bases react with each other. Today, acids and bases are defined in more precise ways that are useful when studying their characteristics.

ExplorerBob/287 images/Pixabay

FIGURE 9.1 Acids give rise to the sour taste of citrus fruits.

9.1 The Arrhenius Theory

Learning Objective 1 Write reaction equations that illustrate Arrhenius acid–base behavior.

In 1887, Swedish chemist Svante Arrhenius proposed a theory dealing with electrolytic dissociation. He defined an **acid** as a substance that dissociates when dissolved in water and produces hydrogen ions (H^+). Similarly, a **base** is a substance that dissociates and releases hydroxide ions (OH^-). Hydrogen chloride (HCl) and sodium hydroxide (NaOH) are examples of an Arrhenius acid and base, respectively. They dissociate in water as follows:

Arrhenius acid Any substance that provides H^+ ions when dissolved in water.

Arrhenius base Any substance that provides OH^- ions when dissolved in water.

$$HCl(aq) \rightarrow H^+(aq) + Cl^-(aq) \tag{9.1}$$

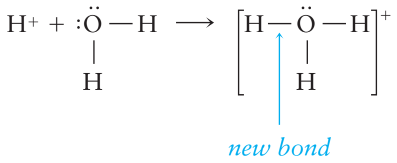
$$NaOH(aq) \rightarrow Na^+(aq) + OH^-(aq) \tag{9.2}$$

Note that the hydrogen ion is a bare proton, the nucleus of a hydrogen atom.

9.2 The Brønsted Theory

Learning Objective 2 Write reaction equations that illustrate Brønsted acid–base behavior, and identify Brønsted acids and bases from written reaction equations.

Arrhenius did not know that free hydrogen ions cannot exist in water. They covalently bond with water molecules to form hydronium ions (H_3O^+). The water molecules provide both electrons used to form the covalent bond:



$$H^+ + :\ddot{O}(H)-H \longrightarrow \left[H-\ddot{O}(H)-H\right]^+ \tag{9.3}$$

Brønsted acid Any hydrogen-containing substance that is capable of donating a proton (H^+) to another substance.

Brønsted base Any substance that is capable of accepting a proton (H^+) from another substance.

Or, more simply,

$$H^+(aq) + H_2O(\ell) \rightarrow H_3O^+(aq) \tag{9.4}$$

In 1923, Johannes Brønsted in Denmark and Thomas Lowry in England proposed an acid–base theory that took into account this behavior of hydrogen ions. They defined an **acid** as any hydrogen-containing substance that donates a proton (hydrogen ion) to another substance and a **base** as any substance that accepts a proton.

In conformity with this theory, the acidic behavior of covalently bonded HCl molecules (see **Figure 9.2**) in water is written

$$HCl(aq) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + Cl^-(aq) \tag{9.5}$$

2099
HYDROCHLORIC ACID
35% w/w
HYDROCHLORIC ACID
35% w/w
2019
HCHLORIC ACID CONC

Sara Sadler/Alamy Stock Photo

FIGURE 9.2 Hydrochloric acid, HCl, is also called muriatic acid. The stomach uses HCl to help digest food.

The HCl behaves as a Brønsted acid by donating a proton to a water molecule. The water molecule, by accepting the proton, behaves as a base.

The double arrows of unequal length in Equation 9.5 indicate that the reaction is reversible, with the equilibrium lying far to the right. In actual water solutions, essentially 100% of the dissolved HCl is in the ionic form at equilibrium. Remember, both the forward and the reverse reactions are taking place at equilibrium (see **Section 8.6**). When the reverse reaction occurs, hydronium ions donate protons to chloride ions to form HCl and H_2O molecules. Thus, H_3O^+ behaves as a Brønsted acid, and Cl^- behaves as a Brønsted base. We see from this discussion that when a substance like HCl behaves as a Brønsted acid by donating a proton, the species that remains (Cl^-) is a Brønsted base. The Cl^- is called the **conjugate base** of HCl. Every Brønsted acid and the base formed when it donates a proton is called a **conjugate acid–base pair**. Thus, in Equation 9.5, we see that HCl and Cl^- form a conjugate acid–base pair, as do H_3O^+ and H_2O for the reverse reaction. Notice that the acid and base in a conjugate acid–base pair differ only by a proton, H^+.

conjugate base The species remaining when a Brønsted acid donates a proton.

conjugate acid–base pair A Brønsted acid and its conjugate base.

Example 9.1 Identifying Brønsted Acids and Bases

Identify all Brønsted acids, bases, and acid–base conjugate pairs in the reactions represented by the following equations:

a. $HNO_3(aq) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + NO_3^-(aq)$
b. $HClO_4(aq) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + ClO_4^-(aq)$
c. $NH_3(aq) + H_2O(\ell) \rightleftharpoons NH_4^+(aq) + OH^-(aq)$

Solution

a. Nitric acid, HNO_3, behaves as a Brønsted acid by donating a proton to H_2O, a base, in the forward reaction. In the reverse reaction, H_3O^+, the conjugate acid of H_2O, donates a proton to NO_3^-, the conjugate base of HNO_3. In summary, the Brønsted acids are HNO_3 and H_3O^+, the Brønsted bases are H_2O and NO_3^-, and the conjugate acid–base pairs are HNO_3/NO_3^- and H_3O^+/H_2O:

$$\underset{\text{acid}}{HNO_3(aq)} + \underset{\text{base}}{H_2O(\ell)} \rightleftharpoons \underset{\text{acid}}{H_3O^+(aq)} + \underset{\text{base}}{NO_3^-(aq)}$$

conjugate pair

conjugate pair

b. Similarly, perchloric acid ($HClO_4$) is a Brønsted acid, and H_2O is a Brønsted base (forward reaction). Also, H_3O^+ is a Brønsted acid, and the perchlorate ion (ClO_4^-) is a Brønsted base (reverse reaction). The conjugate acid–base pairs are $HClO_4/ClO_4^-$ and H_3O^+/H_2O:

$$\underset{\text{acid}}{HClO_4(aq)} + \underset{\text{base}}{H_2O(\ell)} \rightleftharpoons \underset{\text{acid}}{H_3O^+(aq)} + \underset{\text{base}}{ClO_4^-(aq)}$$

conjugate pair

conjugate pair

ENVIRONMENTAL CONNECTIONS **9.1**

Carbon Dioxide in the Oceans

Carbon dioxide (CO_2) is generally recognized as an atmospheric greenhouse gas that contributes to global warming. Concerns are now being raised about the potential adverse impact of dissolved CO_2 on the oceans of the world.

It is estimated that about one-third of the CO_2 produced by burning fossil fuels in our highly industrialized, modern world ends up dissolved in our oceans. This might seem to be a positive development, because it reduces the amount of CO_2 contributing to global warming, but the results of continuing studies raise questions about the possible negative effects of this dissolved CO_2 on ocean ecosystems.

When CO_2 dissolves in water, it reacts with the water to form carbonic acid, H_2CO_3 (Reaction 1). Carbonic acid can dissociate to form H^+ and HCO_3^- (Reaction 2).

1. $CO_2\ (g) + H_2O\ (\ell) \leftrightarrows H_2CO_3(aq)$
2. $H_2CO_3\ (aq) \leftrightarrows H^+\ (aq) + HCO_3^-(aq)$

As the H^+ ions increase the acidity of the water, they have a side effect of reducing the concentration of carbonate ions (CO_3^{2-}), which are the building blocks of shells and skeletons. It is feared that such reductions will interfere with the growth and survival of carbonate-using organisms ranging in size from tiny phytoplankton that serve as major food sources for fish and marine mammals, to corals, the animals responsible for building huge coral reefs, the largest biological structures in the world.

Scientific research results such as these give us another reason to pause, seriously consider the negative impact of some of our modern practices on the world around us, and maybe even change some of those practices.

c. In this reaction, water donates a proton instead of accepting one. Therefore, H_2O is a Brønsted acid, and ammonia (NH_3), see **Figure 9.3** is a Brønsted base (forward reaction). The ammonium ion (NH_4^+) is an acid, and the hydroxide ion (OH^-) is a base (reverse reaction). Note that an Arrhenius base was a substance that released the OH^-, whereas according to Brønsted, the OH^- is a base. The conjugate acid–base pairs are H_2O/OH^- and NH_4^+/NH_3:

$$\underset{\text{base}}{NH_3(aq)} + \underset{\text{acid}}{H_2O(\ell)} \rightleftharpoons \underset{\text{base}}{OH^-(aq)} + \underset{\text{acid}}{NH_4^+(aq)}$$

conjugate pair

conjugate pair

skynesher/iStock/Getty Images

FIGURE 9.3 Ammonia (NH_3) solutions are good household cleaning agents. Because ammonia evaporates quickly, it is often used in glass-cleaning products to help avoid streaking.

✔ **LEARNING CHECK 9.1** Identify all Brønsted acids, bases, and acid–base conjugate pairs in the reactions represented by the following equations:

a. $HC_2H_3O_2(aq) + H_2O(\ell) \rightleftarrows H_3O^+(aq) + C_2H_3O_2^-(aq)$
b. $NO_2^-(aq) + H_2O(\ell) \rightleftarrows HNO_2(aq) + OH^-(aq)$
c. $HS^-(aq) + H_2O(\ell) \rightleftarrows H_3O^+(aq) + S^{2-}(aq)$

9.3 Naming Acids

Learning Objective 3 Name common acids.

In **Section 4.4**, the rules for naming binary ionic compounds were given. The rules for naming binary covalent compounds and ionic compounds that contain polyatomic ions were discussed in **Section 4.10**. We now conclude our discussion of inorganic nomenclature by giving the rules used to name hydrogen-containing compounds that behave as acids. Examples of the two types of compounds that behave as acids were given in **Section 9.2**. Acids of the first type, represented by HCl, are compounds in which hydrogen is covalently bonded to a nonmetal. In acids of the second type, hydrogen is covalently bonded to a polyatomic ion. An example of the second type is HNO_3.

You probably recognized that HCl is a binary covalent compound that can be named by the rules given in **Section 4.10**. According to those rules, HCl should be named hydrogen chloride. In fact, that is the correct name for the compound HCl that has not been dissolved in water and is represented in reaction equations by the notation HCl(g). Such compounds that have not been dissolved in water are said to be anhydrous (without water). However, when the gas is dissolved in water and represented in equations by the notation HCl(aq), it behaves as an acid and is given another name. The following rules are used to name acidic water solutions of such compounds:

1. The word *hydrogen* in the anhydrous compound name is dropped.
2. The prefix *hydro-* is attached to the stem of the name of the nonmetal that is combined with hydrogen.
3. The suffix *-ide* on the stem of the name of the nonmetal that is combined with hydrogen is replaced with the suffix *-ic*.
4. The word *acid* is added to the end of the name as a separate word.

Example 9.2 Naming Acids

Determine the name that would be given to each of the following binary covalent compounds in the anhydrous form:

a. HCl (stomach acid)
b. H_2S (a gas produced when some sulfur-containing foods such as eggs decay; see **Figure 9.4**)

Yongyut Kumsri/Shutterstock.com

FIGURE 9.4 Hydrogen sulfide (H_2S) is found naturally in hot springs, crude petroleum, and natural gas.

Solution

a. The name of the anhydrous compound was given above as hydrogen chloride. The name of the water solution is obtained by dropping *hydrogen* from the anhydrous compound name and adding the prefix *hydro-* to the stem *chlor*. The suffix *-ide* on the stem *chlor* is replaced by the suffix *-ic* to give the name *hydrochloric*. The word *acid* is added, giving the final name *hydrochloric acid* for the water solution.
b. According to the rules of **Section 4.10**, the anhydrous compound name is hydrogen sulfide. The first two steps in obtaining the name of the water solution are to drop *hydrogen* and to add the prefix *hydro-* to the stem *sulf*. However, in acids involving sulfur as the nonmetal combined with hydrogen, the stem *sulf* is replaced by the entire name *sulfur* for pronunciation reasons. The next steps involve dropping the suffix *-ide,* adding the suffix *-ic*, and adding the word *acid*. The resulting name of the water solution is *hydrosulfuric acid*.

✔ **LEARNING CHECK 9.2** Determine the name that would be given to each of the following binary covalent compounds in the hydrous and anhydrous form:

a. HI
b. HBr

Acids of the second type, in which hydrogen is covalently bonded to a polyatomic ion, have the same name in the anhydrous form and in the form of water solutions. The names for these acids are based on the name of the polyatomic ion to which the hydrogen is bonded. The rules are as follows:

1. All hydrogens that are written as the first part of the formula of the acid are removed. The hydrogens are removed in the form of H^+ ions.
2. The polyatomic ion that remains after the H^+ ions are removed is named by referring to sources such as **Table 4.7**.
3. When the remaining polyatomic ion has a name ending in the suffix *-ate,* the suffix is replaced by the suffix *-ic,* and the word *acid* is added.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

4. When the remaining polyatomic ion has a name ending in the suffix *-ite,* the suffix is replaced by the suffix *-ous,* and the word *acid* is added.
5. If the polyatomic ion contains sulfur or phosphorus, the stems *-sulf* or *-phosph* that remain in Steps 3 or 4, when the suffixes *-ate* or *-ite* are replaced, are expanded for pronunciation reasons to *-sulfur* and *-phosphor* before the suffixes *-ic* or *-ous* are added.

Example 9.3 Naming Phosphorus-Containing Acids

Compounds derived from the acid H_3PO_4 serve numerous important functions in the body, including the control of acidity in urine and body cells and the storage of energy in the form of ATP. Name this important acid.

Solution

The removal of the three H^+ ions leaves behind the PO_4^{3-} polyatomic ion. This ion is named the phosphate ion in **Table 4.7**. According to Rules 1–4, the suffix *-ate* is replaced by the suffix *-ic* to give the name *phosphic acid.* However, Rule 5 must be used for this phosphorus-containing acid. The stem is expanded to *phosphor* to give the final name, *phosphoric acid.*

✓ **LEARNING CHECK 9.3** The acid H_2CO_3 is involved in many processes in the body, including the removal of CO_2 gas produced by cellular metabolism and the control of the acidity of various body fluids. Name this important acid.

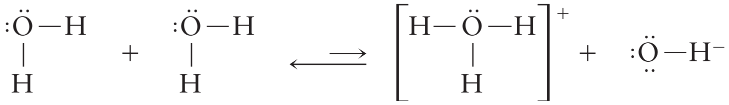
9.4 The Self-Ionization of Water

Learning Objective 4 Do calculations using the concept of the self-ionization of water.

In Examples 9.1a and b, water behaved as a Brønsted base. In Example 9.1c, it was a Brønsted acid. But what happens when only pure water is present? The answer is that water behaves as both an acid and a base and undergoes a self- or auto-ionization. The equation representing this self-ionization is:

$$H_2O(\ell) + H_2O(\ell) \rightleftarrows H_3O^+(aq) + OH^-(aq) \qquad (9.6)$$

or

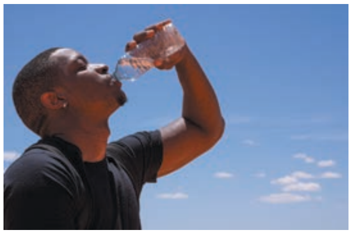


$$\begin{array}{c}:\ddot{O}-H\\ |\\ H\end{array} + \begin{array}{c}:\ddot{O}-H\\ |\\ H\end{array} \rightleftarrows \left[\begin{array}{c}H-\ddot{O}-H\\ |\\ H\end{array}\right]^+ + :\underset{..}{\ddot{O}}-H^-$$

The transfer of a proton from one water molecule (the acid) to another (the base) causes one H_3O^+ and one OH^- to form. Therefore, in pure water the concentrations of H_3O^+ and OH^- must be equal. At 25°C these concentrations are 10^{-7} mol/L (M). Thus, the equilibrium position is far to the left, as indicated by the arrows in Equation 9.6. Unless noted otherwise, all concentrations and related terms in this chapter are given at 25°C.

The term **neutral** is used to describe any water solution (see **Figure 9.5**) in which the concentrations of H_3O^+ and OH^- are equal. Thus, pure water is neutral because each liter of pure water contains 10^{-7} mol H_3O^+ and 10^{-7} mol OH^-, at equilibrium. Although all water solutions are not necessarily neutral, it is true that in any solution that contains water, the product of the molar concentrations of H_3O^+ and OH^- is a constant. This becomes apparent by writing the equilibrium expression for Reaction 9.6:

$$K = \frac{[H_3O^+][OH^-]}{[H_2O][H_2O]} = \frac{[H_3O^+][OH^-]}{[H_2O]^2} \qquad (9.7)$$



Chris971/Shutterstock.com

FIGURE 9.5 Pure water is considered to be neutral, neither an acid nor a base.

neutral A term used to describe any water solution in which the concentrations of H_3O^+ and OH^- are equal. Also, a water solution with pH = 7.

This expression contains the square of the concentration of water in the denominator. However, only a tiny amount of water actually reacts to form H_3O^+ and OH^- (10^{-7} mol/L), so the concentration of water remains essentially constant. Rearrangement of Equation 9.7 gives

$$K[H_2O]^2 = [H_3O^+][OH^-] \tag{9.8}$$

This equation may be written as

$$K[H_2O]^2 = K_w = [H_3O^+][OH^-] \tag{9.9}$$

ion product of water The equilibrium constant for the dissociation of pure water into H_3O^+ and OH^-.

acidic solution A solution in which the concentration of H_3O^+ is greater than the concentration of OH^-. Also, a solution in which pH is less than 7.

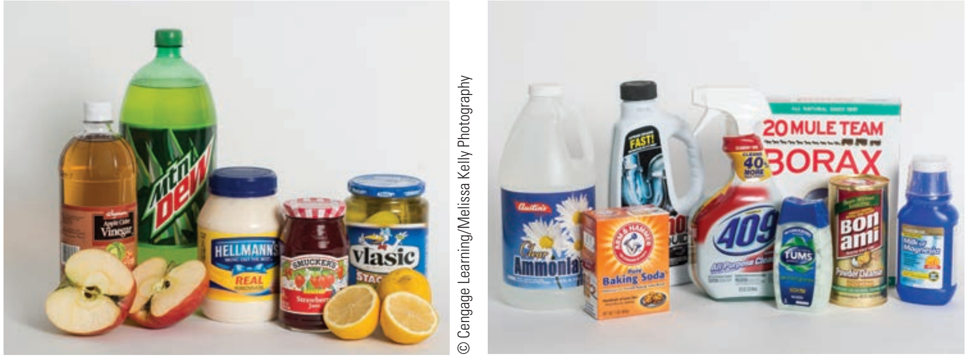
basic or alkaline solution A solution in which the concentration of OH^- is greater than the concentration of H_3O^+. Also, a solution in which pH is greater than 7.

where K_w is a new constant called the **ion product of water**. It is a constant because it is equal to the product of two constants, K and $[H_2O]^2$. At 25°C, K_w can be evaluated from the measured values of $[H_3O^+]$ and $[OH^-]$ in pure water.

$$\begin{aligned} K_w &= [H_3O^+][OH^-] = (1.0 \times 10^{-7}\,\text{mol/L})(1.0 \times 10^{-7}\,\text{mol/L}) \\ &= 1.0 \times 10^{-14}\,(\text{mol/L})^2 \end{aligned} \tag{9.10}$$

Equation 9.10 is valid not only for pure water but for any solution in which water is the solvent. Note that we are including units for equilibrium constants in this discussion. This makes the calculation of concentrations easier to follow and understand.

A solution is classified as **acidic** when the concentration of H_3O^+ is greater than the concentration of OH^-. In a **basic** or **alkaline solution**, the concentration of OH^- is greater than that of H_3O^+. However, the product of the molar concentrations of H_3O^+ and OH^- will be 1.0×10^{-14} $(\text{mol/L})^2$ in either case. Many acidic and basic materials are found in the home (see **Figure 9.6**).



© Cengage Learning/Melissa Kelly Photography

© Cengage Learning/Melissa Kelly Photography

a Acidic materials found at home.

b Basic or alkaline materials found at home.

FIGURE 9.6 Acidic and basic materials are common in the home. Look at the photos, and note a single category to which most of the acidic materials belong, and one to which most of the basic materials belong.

Example 9.4 Solution Classifications and Calculations

Classify each of the following solutions as acidic, basic, or neutral. Calculate the molar concentration of the ion whose concentration is not given.

a. $[H_3O^+] = 1.0 \times 10^{-5}$ mol/L

b. $[OH^-] = 1.0 \times 10^{-6}$ mol/L

Solution a.

STEP 1: Examine the question for what is given and what is unknown.

Given: $[H_3O^+] = 1.0 \times 10^{-5}$ mol/L Unknown: $[OH^-] = ?$

STEP 2: Identify a formula that links the given and unknown terms.

Key Equation 9.10: $[H_3O^+][OH^-] = 1.0 \times 10^{-14}\,(\text{mol/L})^2$

STEP 3: Enter the data into the formula.

$$(1.0 \times 10^{-5}\,\text{mol/L})[OH^-] = 1.0 \times 10^{-14}\,(\text{mol/L})^2$$

Rearranging gives

$$[OH^-] = \frac{1.0 \times 10^{-14}\ (mol/L)^2}{1.0 \times 10^{-5}\ mol/L} = 1 \times 10^{-9}\ mol/L$$

The solution is acidic because the $[H_3O^+]$ is greater than the $[OH^-]$; 1.0×10^{-5} is greater than 1.0×10^{-9}.

STEP 4: Check to see whether the answer makes sense.

Yes. The sum of −5 and −9 is −14 (Key Equation 9.10).

Solution b.

STEP 1: Examine the question for what is given and what is unknown.

Given: $[OH^-] = 1 \times 10^{-6}$ mol/L Unknown: $[H_3O^+] = ?$

STEP 2: Identify a formula that links the given and the unknown terms.

Key Equation 9.10: $[H_3O^+][OH^-] = 1.0 \times 10^{-14}\ (mol/L)^2$

STEP 3: Enter the data into the formula.

$$[H_3O^+](1.0 \times 10^{-6}\ mol/L) = 1.0 \times 10^{-14}\ (mol/L)^2$$

Rearranging gives

$$[H_3O^+] = \frac{1.0 \times 10^{-14}\ (mol/L)^2}{1.0 \times 10^{-6}\ mol/L} = 1.0 \times 10^{-8}\ mol/L$$

The solution is basic because the $[OH^-]$ is greater than the $[H_3O^+]$; 1.0×10^{-6} is greater than 1.0×10^{-8}.

STEP 4: Check to see whether the answer makes sense.

Yes. The sum of −6 and −8 is −14 (Key Equation 9.10).

✔ **LEARNING CHECK 9.4** Classify each of the following solutions as acidic, basic, or neutral. Calculate the molarity of the ion whose concentration is not given.

a. Milk of Magnesia, used to relieve indigestion and heartburn, has $[OH^-] = 1 \times 10^{-5}$ mol/L
b. The nonsteroidal antiinflammatory drug (NSAID) aspirin in water gives $[H_3O^+] = 1 \times 10^{-5}$ mol/L

9.5 The pH Concept

Learning Objective 5 Do calculations using the pH concept.

In **Section 9.4**, you learned that the concentration of H_3O^+ in pure water is 1.0×10^{-7} M. Chemists, technologists, and other laboratory personnel routinely work with solutions in which the H_3O^+ concentration may be anywhere from 10 to 10^{-14} M. Because of the inconvenience of working with numbers that extend over such a wide range, chemists long ago adopted a shortcut notation known as the pH. Mathematically, the **pH** is defined in terms of the negative logarithm (log) of $[H_3O^+]$ by the following two equations

pH The negative logarithm of the molar concentration of H_3O^+ in a solution.

$$pH = -\log[H_3O^+] \tag{9.11}$$

$$[H_3O^+] = 1 \times 10^{-pH} \tag{9.12}$$

Thus, pH is simply the negative of the exponent used to express the hydrogen ion concentration in moles per liter.

JGI/Jamie Grill/Tetra images/Getty Images

FIGURE 9.7 Milk has a pH of around 6.5 to 6.7, which makes it slightly acidic.

Example 9.5 Calculating pH Values

Cow's milk is slightly acidic (pH 6.5–6.7; see **Figure 9.7**). Let's compare with other common beverages. Express the following ion concentrations in terms of pH:

a. Nondairy milks like rice, soy, and almond have $[H_3O^+] = 1 \times 10^{-6}$ mol/L

b. Orange juice has $[OH^-] = 1 \times 10^{-10}$ mol/L

Solution a.

STEP 1: Examine the question for what is given and what is unknown.

Given: $[H_3O^+] = 1 \times 10^{-6}$mol/L Unknown: pH = ?

STEP 2: Identify a formula that links the given and unknown terms.

Key Equation 9.12: $[H_3O^+] = 1 \times 10^{-pH}$

STEP 3: Enter the data into the formula.

$$1 \times 10^{-6} \text{ mol/L} = 1 \times 10^{-pH}; \text{ pH} = 6$$

STEP 4: Check to see whether the answer makes sense.

Yes. The pH is simply the exponent of the $[H_3O^+]$.

Solution b.

STEP 1: Examine the question for what is given and what is unknown.

Given: $[OH^-] = 1 \times 10^{-10}$ mol/L Unknown: pH = ?

To find pH, $[H_3O^+]$ must first be calculated.

STEP 2: Identify a formula that links the given and what is unknown.

Key Equation 9.10: $[H_3O^+][OH^-] = 1.0 \times 10^{-14}(\text{mol/L})^2$

and then

$$\text{Key Equation 9.12: } [H_3O^+] = 1 \times 10^{-pH}$$

STEP 3: Enter the data into the formula.

$$[H_3O^+](1 \times 10^{-10} \text{ mol/L}) = 1.0 \times 10^{-14} (\text{mol/L})^2$$

Rearranging gives

$$[H_3O^+] = \frac{1.0 \times 10^{-14} (\text{mol/L})^2}{1 \times 10^{-10} \text{ mol/L}} = 1 \times 10^{-4} \text{ mol/L}$$

Now enter that value for $[H_3O^+]$ into Key Equation 9.12.

$$1 \times 10^{-4} = 1 \times 10^{-pH}; \text{ pH} = 4$$

STEP 4: Check to see whether the answer makes sense.

Yes. The pH is the exponent of the $[H_3O^+]$.

✔ LEARNING CHECK 9.5 Express the following concentrations in terms of pH.

a. A urine sample has $[H_3O^+] = 1 \times 10^{-6}$

b. A household ammonia cleaner has $[OH^-] = 1 \times 10^{-3}$

The pH value of 6.0 obtained in Example 9.5a corresponds to a solution in which the H_3O^+ concentration is greater than the OH^- concentration. Thus, the solution is acidic. Any solution with a pH less than 7 is classified as acidic. Any solution with a pH greater than 7 is classified as basic or alkaline. The pH values of some familiar solutions are given in **Table 9.1**. Among them, the most acidic is battery acid (see **Figure 9.8**).

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

TABLE 9.1 Relationship between $[H_3O^+]$, $[OH^-]$, and pH

	$[H_3O^+]$	$[OH^-]$	pH	Examples (solids are dissolved in water)
	10^0	10^{-14}	0	Battery acid
	10^{-1}	10^{-13}	1	Gastric juice
	10^{-2}	10^{-12}	2	Lemon juice
	10^{-3}	10^{-11}	3	Vinegar, carbonated drink Aspirin
	10^{-4}	10^{-10}	4	Orange juice Apple juice
	10^{-5}	10^{-9}	5	Black coffee
	10^{-6}	10^{-8}	6	Normal urine (average value) Milk, liquid dishwashing detergent
Neutral	10^{-7}	10^{-7}	7	Saliva, pure water Blood
	10^{-8}	10^{-6}	8	Soap (not synthetic detergent) Baking soda Phosphate-containing detergent
	10^{-9}	10^{-5}	9	Milk of magnesia Powdered household cleanser
	10^{-10}	10^{-4}	10	Phosphate-free detergent
	10^{-11}	10^{-3}	11	Household ammonia
	10^{-12}	10^{-2}	12	Liquid household cleaner
	10^{-13}	10^{-1}	13	Oven cleaner
	10^{-14}	10^0	14	Liquid drain cleaner

Zynatis/Shutterstock.com

FIGURE 9.8 The acid in automobile lead-acid batteries is sulfuric acid, H_2SO_4, and is highly corrosive.

Example 9.6 pH Calculations

Perspiration is found at moderately acidic to neutral pH levels, typically between 4.5 and 7.0. Determine H_3O^+ and OH^- molar concentrations that correspond to a perspiration pH of 6.0.

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: pH = 6.0 Unknown: $[H_3O^+] = ?$ and $[OH^-] = ?$

STEP 2 Identify a formula that links the given and unknown terms.

Calculate $[H_3O^+]$ first, using Key Equation 9.12: $[H_3O^+] = 1.0 \times 10^{-pH}$.
To calculate $[OH^-]$, use Key Equation 9.10: $[H_3O^+][OH^-] = 1.0 \times 10^{-14}\,(\text{mol/L})^2$

STEP 3 Enter the data into the formulas.

$$[H_3O^+] = 1.0 \times 10^{-pH} = 1.0 \times 10^{-6}\ \text{mol/L}$$

Enter the $[H_3O^+]$ into Key Equation 9.10:

$$1.0 \times 10^{-6}\ \text{mol/L}\,[OH^-] = 1.0 \times 10^{-14}\,(\text{mol/L})^2$$

Rearranging gives

$$[OH^-] = \frac{1.0 \times 10^{-14}\,(\text{mol/L})^2}{1.0 \times 10^{-6}\ \text{mol/L}} = 1.0 \times 10^{-8}\ \text{mol/L}$$

STEP 4 Check to see whether the answer makes sense.

Yes. The sum of −8 and −6 is −14 (Key Equation 9.10).

Keith Homan/Alamy Stock Photo

FIGURE 9.9 Apple cider vinegar is made from fermented apple juice and gets its sour taste due to the presence of acetic acid.

✔ LEARNING CHECK 9.6 Determine the $[H_3O^+]$ and $[OH^-]$ values that correspond to the following pH values:

a. Gastric juice has a pH = 1.0
b. A laundry detergent has pH = 10.0

It is apparent from **Table 9.1** that not all solutions have pH values that are neat whole numbers. For example, the pH of vinegar (see **Figure 9.9**) is about 3.3. How do we deal with such numbers? The H_3O^+ concentration of vinegar could be written $1 \times 10^{-3.3}$, but it is not convenient to work with exponents that are not whole numbers. When exact values are not needed, the pH, $[H_3O^+]$, and so on can be expressed as a range. Thus, the H_3O^+ concentration of vinegar is between 1×10^{-3} and 1×10^{-4} mol/L. Similarly, a solution with $[H_3O^+] = 2 \times 10^{-5}$ mol/L has a pH between 4 and 5.

When more exact values are needed, we must work with logarithms. This is most easily done by using a hand calculator. A hydrogen ion concentration is converted to pH by taking the logarithm and changing its sign. **Table 9.2** gives the steps of a typical calculator procedure (what button is pushed, etc.) and a typical calculator readout or display for the conversion of $[H_3O^+] = 3.6 \times 10^{-4}$ mol/L into pH. The pH from **Table 9.2** would be recorded as 3.44.

TABLE 9.2 Calculating pH from Molarity with a Scientific Calculator

Step	Example	Calculator Procedure		Calculator Display
Enter $[H_3O^+]$ expressed in mol/L	3.6×10^{-4}	3 . 6	3 . 6	3.6
		enter exponent	EE or EXP	3.6 00
		4	4	3.6 04
		change sign	+/-	3.6 −04
Take logarithm		log	log	−3.4437
Change sign		change sign	+/-	3.4437

✔ LEARNING CHECK 9.7 Blood plasma is the liquid component of blood that holds the blood cells in whole blood in suspension. A sample of blood plasma has $[H_3O^+] = 4.0 \times 10^{-8}$. What is the pH of the sample?

Calculators can also be used to convert pH values into corresponding molar concentrations. The steps are given in **Table 9.3** for the conversion of a pH value of 5.92 into $[H_3O^+]$. As shown in **Table 9.3**, a pH of 5.92 corresponds to a $[H_3O^+]$ of 1.2×10^{-6} mol/L. Note that

TABLE 9.3 Calculating Molarity from pH with a Calculator

Step	Example	Calculator Procedure		Calculator Display
Enter pH	5.92	5 . 9 2	5 . 9 2	5.92
Change sign		Change sign	+/-	−5.92
Take antilog		10^x button	10^x	0.000001202
(other ways to take antilog)		or INV button or 2^{nd} function button	INV 2^{nd}	
(other ways to take antilog, continued)		then log button	log	0.000001202
Convert to scientific notation		(consult your calculator manual; one way is INV or 2^{nd} function then Sci button)		1.2 −06

the number of figures to the right of the decimal in a pH value should be the same as the number of significant figures in the $[H_3O^+]$ value. Thus, the two figures to the right of the decimal in pH = 5.92 is reflected in the two significant figures in $[H_3O^+] = 1.2 \times 10^{-6}$ mol/L.

✔ **LEARNING CHECK 9.8** The pH of the blood is normally between 7.35 and 7.45. If a lower blood pH (a condition known as acidosis) of 7.20 is measured, what is the H_3O^+ concentration?

9.6 Properties of Acids

Learning Objective 6 Write reaction equations that illustrate the characteristic reactions of acids.

Acids and bases are used so often in most laboratories that stock solutions are kept readily available at each work space. The common solutions, their concentrations, and label designations are given in **Table 9.4**.

TABLE 9.4 Common Laboratory Acids and Bases

Name	Formula	Label Concentration	Molarity
Acids			
Acetic acid	$HC_2H_3O_2$	Glacial	18
Acetic acid	$HC_2H_3O_2$	Dilute	6
Hydrochloric acid	HCl	Concentrated	12
Hydrochloric acid	HCl	Dilute	6
Nitric acid	HNO_3	Concentrated	16
Nitric acid	HNO_3	Dilute	6
Sulfuric acid	H_2SO_4	Concentrated	18
Sulfuric acid	H_2SO_4	Dilute	3
Bases			
Aqueous ammonia[a]	NH_3	Concentrated	15
Aqueous ammonia	NH_3	None usually given	6
Sodium hydroxide	NaOH	None usually given	6

[a] Often erroneously called ammonium hydroxide and given the formula NH_4OH.

Example 9.7 Solution Preparation by Dilution

If a medication order is written in a hospital for a solution concentration that is not commercially available, then a health professional will carry out a dilution of a stock solution on hand. Describe how you would make 250 mL of 1.0 M HNO_3 using a (6.0 M) HNO_3 stock solution.

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: 250 mL of 1.0 M HNO_3 Unknown: mL of 6.0 M HNO_3 = ?

STEP 2 Identify a formula that links the given and unknown terms.

Key Equation 7.9: $(C_c)(V_c) = (C_d)(V_d)$

STEP 3 Enter the data into the formula.

$$(1.0\text{ M})(250\text{ mL}) = (6.0\text{ M})(V_d)$$

Rearranging gives

$$V_d = \frac{(1.0\ \cancel{\text{M}})(250\text{ mL})}{6.0\ \cancel{\text{M}}} = 41.7\text{ mL}$$

Rounding to two significant figures gives 42 mL. Thus, 42 mL of 6.0 M HNO_3 is measured with a graduated cylinder, and this is added to 208 mL of distilled water that has also been measured with a graduated cylinder.

STEP 4 Check to see whether the answer makes sense.

Yes. If 42 mL of solution is diluted to a volume of 250 mL, that would reduce the concentration of the solution by a factor of 6 (6.0 M to 1.0 M).

✔ **LEARNING CHECK 9.9** Describe how you would prepare 500 mL of 3.0 M aqueous ammonia using a concentrated NH_3 stock solution (see **Table 9.4**).

Different acids have different properties that make some more practical than others for specific uses. However, all acids have certain properties in common. Two of these were mentioned earlier—all acids taste sour and produce H_3O^+ ions when dissolved in water. In addition, all acids undergo characteristic double-replacement reactions with solid oxides, hydroxides, carbonates, and bicarbonates (see **Figures 9.10** and **9.11**).

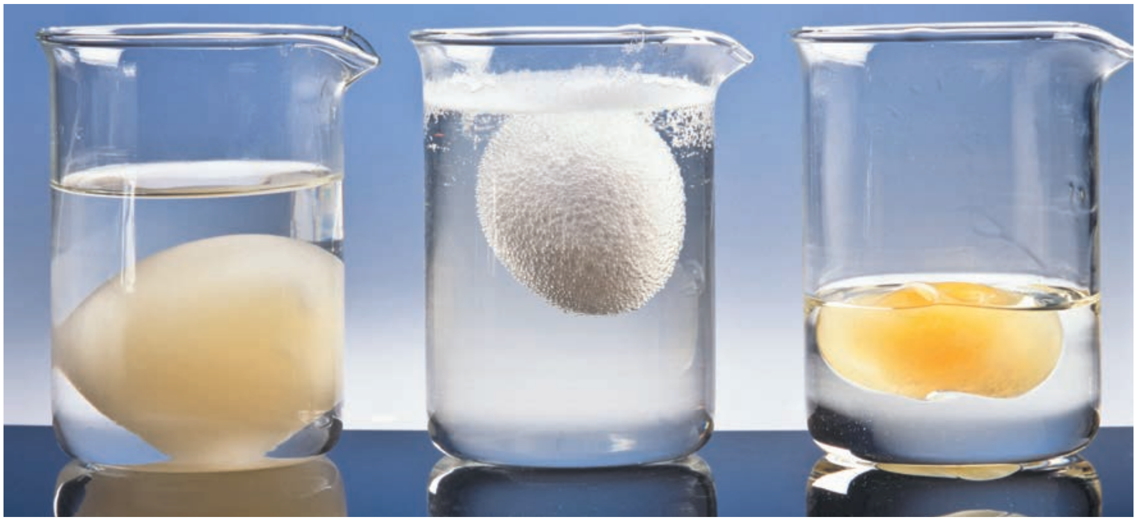

Charles D. Winters/Science Source

FIGURE 9.10 The reaction of hydrochloric acid with a natural form of $CaCO_3$ (eggshell). What gas is produced?

$$\underset{\text{copper oxide}}{2HCl(aq) + CuO(s)} \longrightarrow CuCl_2(aq) + H_2O(\ell) \quad (9.13)$$

$$2HCl(aq) + \underset{\text{calcium hydroxide}}{Ca(OH)_2(s)} \longrightarrow CaCl_2(aq) + 2H_2O(\ell) \quad (9.14)$$

$$2HCl(aq) + \underset{\text{calcium carbonate}}{CaCO_3(s)} \longrightarrow CaCl_2(aq) + CO_2(g) + H_2O(\ell) \quad (9.15)$$

$$2HCl(aq) + \underset{\text{strontium bicarbonate}}{Sr(HCO_3)_2(s)} \longrightarrow SrCl_2(aq) + 2CO_2(g) + 2H_2O(\ell) \quad (9.16)$$

A.Luna/Shutterstock.com

FIGURE 9.11 Marble statues, comprised of calcium carbonate, $CaCO_3$, can deteriorate over time as the natural form of carbonate reacts with acids in polluted air.

Notice that the preceding reactions are written using molecular equations (see **Section 5.7**).

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Reactions involving ionic substances can also be written as total ionic equations or net ionic equations. Equation 9.13 is written in total ionic form in Equation 9.17.

$$\underbrace{2\mathrm{H}^+(aq)+2\mathrm{Cl}^-(aq)}_{2\mathrm{HCl}}+\mathrm{CuO}(s)\longrightarrow \underbrace{\mathrm{Cu}^{2+}(aq)+2\mathrm{Cl}^-(aq)}_{\mathrm{CuCl}_2}+\mathrm{H}_2\mathrm{O}(\ell) \tag{9.17}$$

We see that the chloride ions are spectator ions, so a net ionic equation can be written as shown in Equation 9.18.

$$2\mathrm{H}^+(aq) + \mathrm{CuO}(s) \rightarrow \mathrm{Cu}^{2+}(aq) + \mathrm{H}_2\mathrm{O}(\ell) \tag{9.18}$$

The general nature of the reaction is emphasized in the net ionic form because the H^+ could come from any acid.

Remember that correctly written molecular equations must have their atoms balanced (see **Section 5.1**). Total ionic and net ionic equations must also have their atoms balanced, but in addition the total charges on each side of the equation must balance. In Equation 9.18, for example, the two H^+ ions provide two positive charges on the left, which are balanced by the two positive charges of Cu^{2+} on the right.

Example 9.8 Writing Ionic Equilibrium Equations

Equations 9.14 and 9.15 involve Ca^{2+} and Cl^- ions, which are commonly found in blood plasma. Write each of these equations in total ionic and net ionic forms.

Solution

In Equation 9.14, HCl and $CaCl_2$ are soluble and ionizable.

Total ionic: $2\mathrm{H}^+(aq) + 2\mathrm{Cl}^-(aq) + \mathrm{Ca(OH)}_2(s) \rightarrow \mathrm{Ca}^{2+}(aq) + 2\mathrm{Cl}^-(aq) + 2\mathrm{H}_2\mathrm{O}(\ell)$

The Cl^- is a spectator ion.

Net ionic: $2\mathrm{H}^+(aq) + \mathrm{Ca(OH)}_2(s) \rightarrow \mathrm{Ca}^{2+}(aq) + 2\mathrm{H}_2\mathrm{O}(\ell)$

In Equation 9.15, HCl and $CaCl_2$ are soluble and ionizable.

Total ionic: $2\mathrm{H}^+(aq) + 2\mathrm{Cl}^-(aq) + \mathrm{CaCO}_3(s) \rightarrow \mathrm{Ca}^{2+}(aq) + 2\mathrm{Cl}^-(aq) + \mathrm{CO}_2(g) + \mathrm{H}_2\mathrm{O}(\ell)$

Again, Cl^- is a spectator ion.

Net ionic: $2\mathrm{H}^+(aq) + \mathrm{CaCO}_3(s) \rightarrow \mathrm{Ca}^{2+}(aq) + \mathrm{CO}_2(g) + \mathrm{H}_2\mathrm{O}(\ell)$

✓ **LEARNING CHECK 9.10** Write Equation 9.16 in total and net ionic forms. Consider HCl and $SrCl_2$ as soluble and ionizable.

Another property of acids is their ability to react with (and dissolve) certain metals to yield hydrogen gas. This is a redox reaction (see **Section 5.3**), as evidenced by the change in the oxidation number of hydrogen as the reaction takes place. In compounds such as acids, hydrogen has an oxidation number of +1. In hydrogen gas, the oxidation number is 0 (**Section 5.3**). Thus, hydrogen is reduced during the reaction, and, as shown by Equations 9.19 and 9.20, the metal is oxidized. The ability to reduce hydrogen ions to hydrogen gas is not the same for all metals. Some are such strong reducing agents that they can react with hydrogen ions at very low concentrations such as that found in water. Others are so weak as reducing agents that they cannot react with H^+ at the high concentration found in concentrated acids. These tendencies are represented by the

activity series A tabular representation of the tendencies of metals to react with H^+.

activity series of metals shown in **Table 9.5**. The higher a metal is in the series, the more active it is as a reducing agent. Some typical reactions are given in Equations 9.19 and 9.20 (see **Figure 9.12**).

TABLE 9.5 The Activity Series of the Metals

Metal	Symbol	Comments
Potassium	K	React violently with cold water
Sodium	Na	
Calcium	Ca	Reacts slowly with cold water
Magnesium	Mg	React very slowly with steam, but quite rapidly in higher H^+ concentrations
Aluminum	Al	
Zinc	Zn	
Chromium	Cr	
Iron	Fe	React in moderately high H^+ concentrations
Nickel	Ni	
Tin	Sn	
Lead	Pb	
Copper	Cu	Do not react with H^+
Mercury	Hg	
Silver	Ag	
Platinum	Pt	
Gold	Au	

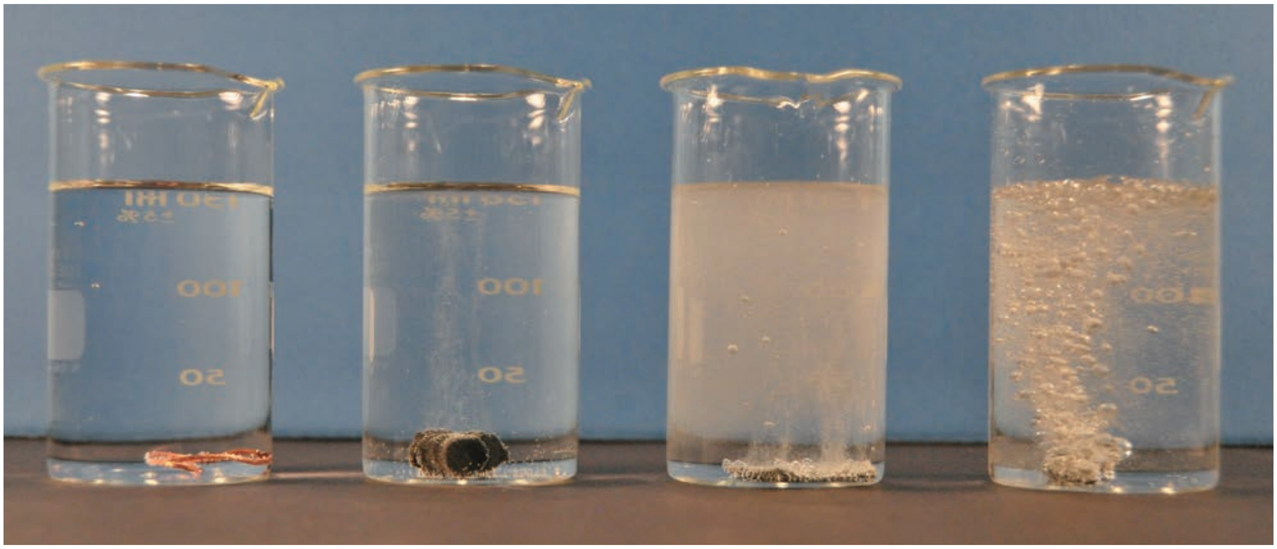

© Jeffrey M. Seager

FIGURE 9.12 Metals vary in their ability to reduce hydrogen ions (H^+) to hydrogen gas (H_2). This difference is apparent when copper, iron, zinc, and magnesium (left to right) are put into hydrochloric acid solution (HCl) of the same molarity. Are these results consistent with **Table 9.5**? Explain.

$$\text{Molecular equation: } Zn(s) + 2HCl(aq) \rightarrow ZnCl_2(aq) + H_2(g) \qquad (9.19)$$

$$\text{Net ionic equation: } Zn(s) + 2H^+(aq) \rightarrow Zn^{2+}(aq) + H_2(g)$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Molecular equation: $2K(s) + 2H_2O(\ell) \rightarrow 2KOH(aq) + H_2(g)$ (9.20)

Net ionic equation: $2K(s) + 2H_2O(\ell) \rightarrow 2K^+(aq) + 2OH^-(aq) + H_2(g)$

✔ **LEARNING CHECK 9.11** Write molecular, total ionic, and net ionic equations to represent the following reactions:

a. Calcium (Ca) with cold water (NOTE: $Ca(OH)_2$ is not soluble in water).
b. Mg with H_2SO_4 (NOTE: $MgSO_4$ is soluble and ionizable in water).

9.7 Properties of Bases

Learning Objective 7 Write reaction equations that represent neutralization reactions between acids and bases.

Solutions containing bases feel soapy or slippery (see **Figure 9.13**) and change the color of litmus from red to blue. Equation 9.14 illustrates their most characteristic chemical property—they react readily with acids. In most of the earliest acid–base reactions studied, the complete reaction of an acid with a base produced a neutral solution. For this reason, such reactions were often called **neutralization reactions** (see below). It is now known that many "neutralization" reactions do not produce neutral solutions (see **Section 9.12**). However, the name for the reactions is still used. More than 20 billion pounds of sodium hydroxide (NaOH) is produced and used in the United States each year. This useful crystalline solid is quite soluble in water and dissociates to form basic solutions.

Richard Bailey/The Image Bank Unreleased/Getty Images

FIGURE 9.13 The slippery feeling of soap is due to the presence of basic substances.

$$NaOH(s) + H_2O(\ell) \rightarrow Na^+(aq) + OH^-(aq) \quad (9.21)$$

neutralization reaction A reaction in which an acid and base react completely, leaving a solution that contains only a salt and water.

The neutralization reaction between NaOH and HCl is

Molecular equation: $HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(\ell)$ (9.22)

Total ionic equation: $H^+(aq) + Cl^-(aq) + Na^+(aq) + OH^-(aq) \rightarrow Na^+(aq) + Cl^-(aq) + H_2O(\ell)$ (9.23)

Net ionic equation: $H^+(aq) + OH^-(aq) \rightarrow H_2O(\ell)$ (9.24)

The molecular equation (9.22) illustrates the following statement, which is a common definition of neutralization: During a neutralization reaction, an acid and a base combine to form a salt and water. (More is said about salts in the next section.) The net ionic form of the equation (9.24) emphasizes on the general nature of neutralization reactions: H^+ ions (from any source) react with OH^- (from any source) to form water.

Bases also react with fats and oils and convert them into smaller, soluble molecules. For this reason, most household cleaning products contain basic substances. For example, lye (NaOH) is the active ingredient in numerous drain cleaners, and many liquid household cleaners contain ammonia.

✔ **LEARNING CHECK 9.12** Write molecular, total ionic, and net ionic equations to represent neutralization reactions between the following acids and bases:

a. HNO_3 and NaOH
b. H_2SO_4 and KOH

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STUDY TOOLS 9.1

Writing Reactions of Acids

As you study this chapter, you will acquire a knowledge of the characteristic reactions of acids and the ability to write balanced equations for the reactions. There are five characteristic reactions:

- General
  Reaction: acid + metal → salt + H_2
  Example: $H_2SO_4(aq) + Zn(s) \rightarrow ZnSO_4(aq) + H_2(g)$
- General
  Reaction: acid + metal oxide → salt + H_2O
  Example: $2HCl(aq) + CuO(s) \rightarrow CuCl_2(aq) + H_2O(\ell)$
- General
  Reaction: acid + metal hydroxide → salt + H_2O
  Example: $H_2SO_4(aq) + 2KOH(aq) \rightarrow K_2SO_4(aq) + 2H_2O(\ell)$
- General
  Reaction: acid + metal carbonate → salt + H_2O + CO_2
  Example: $2HCl(aq) + CaCO_3(s) \rightarrow CaCl_2(aq) + H_2O(\ell) + CO_2(g)$
- General
  Reaction: acid + metal carbonate → salt + H_2O + CO_2
  Example: $2HCl(aq) + Sr(HCO_3)_2(s) \rightarrow SrCl_2(aq) + 2H_2O(\ell) + 2CO_2(g)$

One useful way to remember the reactions is to learn them as general word equations, such as

"An acid plus a metal gives a salt plus hydrogen gas"

rather than as specific equations. If you learn the general word equations and you recognize the starting materials for a reaction (such as an acid and a metal), you will know what the products will be (a salt and H_2 gas).

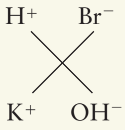
A second approach is to remember that the last four of the general reactions of acids are double-replacement reactions. The formulas of the products of double-replacement reactions can be predicted by simply breaking each reactant into its positive and negative parts and recombining the parts in the other possible way (the positive part of one reactant with the negative part of the other reactant). For example, let's determine the products and the balanced equation for a reaction between H_2SO_4 and KOH. If you remember that H_2SO_4 is an acid and KOH is a base, the general word equation says the products will be a salt and water:

$$H_2SO_4(aq) + KOH(aq) \rightarrow \text{salt}(aq) + H_2O(\ell)$$

H_2SO_4 breaks apart to give H^+ and $SO_4{}^{2-}$; KOH breaks apart to give K^+ and OH^-. If we combine the positive part of the acid (H^+) with the negative part of the base (OH^-), we get the water (H_2O). A similar combination of the positive part of the base (K^+) with the negative part of the acid ($SO_4{}^{2-}$) gives the salt. We must remember that the total charges of the combined parts must add up to 0. Thus, two K^+ will combine with one $SO_4{}^{2-}$ to give the salt K_2SO_4. The balanced equation is

$$H_2SO_4(aq) + 2KOH(aq) \rightarrow K_2SO_4(aq) + 2H_2O(\ell)$$

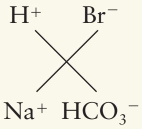
As another example, consider a reaction between HBr and KOH. KBr breaks into H^+ and Br^-. KOH breaks into K^+ and OH^-. Now, switch the parts and recombine:



The products are KBr and H_2O, and the balanced equation is

$$HBr(aq) + KOH(aq) \rightarrow KBr(aq) + H_2O(\ell)$$

For another example, let's try a reaction between HBr and $NaHCO_3$. The word equation predicts that the products should be a salt, water, and carbon dioxide gas. HBr breaks into H^+ and Br^-; $NaHCO_3$ breaks into Na^+ and $HCO_3{}^-$. Now, switch the parts and recombine:



The products are NaBr and H_2CO_3. However, H_2CO_3 is not stable; it decomposes to give H_2O and CO_2, the products predicted earlier. The balanced equation is

$$HBr(aq) + NaHCO_3(aq) \rightarrow NaBr(aq) + H_2O(\ell) + CO_2(g)$$

9.8 Salts

Learning Objective 8 Write reaction equations that illustrate various ways to prepare salts, and do calculations using the concept of an equivalent of salt.

At room temperature, a **salt** is a solid ionic compound that contains the **cation** (positive ion) of a base and the **anion** (negative ion) of an acid. Thus, ordinary table salt (NaCl) contains Na^+, the cation of NaOH, and Cl^-, the anion of HCl (look again at Equation 9.22). Similarly,

salt	A solid crystalline ionic compound at room temperature that contains the cation of a base and the anion of an acid.
cation	A positively charged ion.
anion	A negatively charged ion.

$CuSO_4$ is a salt containing the cation of $Cu(OH)_2$ and the anion of H_2SO_4. You must be careful to think of the term *salt* in a general way (see **Figure 9.14**), and not as representing only table salt (NaCl).

Alena Mozhjer/Shutterstock.com

FIGURE 9.14 Utah's Bonneville Salt Flats consist of deposits of NaCl, $MgCl_2$, and numerous other salts in lesser concentrations.

Some acids and bases are not stable enough to be isolated even though their salts are. For example, carbonic acid (H_2CO_3) cannot be isolated in the pure state. When it forms in water, it promptly decomposes:

$$H_2CO_3(aq) \rightleftharpoons H_2O(\ell) + CO_2(g) \qquad (9.25)$$

Despite this characteristic, salts of carbonic acid, such as Na_2CO_3 and $NaHCO_3$, are quite stable.

It is not necessary to identify the parent acid and base in order to write correct salt formulas or names. Just remember that the cation of a salt can be any positive ion except H^+, and it will usually be a simple metal ion or NH_4^+. The salt anion can be any negative ion except OH^-. Most of the polyatomic anions you will use are given in **Table 4.7**. The rules for naming salts are given in **Sections 4.4** and **4.10**.

As previously observed, salts dissolved in solution are dissociated into ions. The salt can be recovered by evaporating away the water solvent. When this is done carefully, some salts retain specific numbers of water molecules as part of the solid crystalline structure. Such salts are called **hydrates**, and the retained water is called the **water of hydration**. Most hydrates lose all or part of the water of hydration when they are heated to moderate or high temperatures. A number of useful hydrates are given in **Table 9.6**.

hydrate A salt that contains specific numbers of water molecules as part of the solid crystalline structure.

water of hydration Water retained as part of the solid crystalline structure of some salts.

TABLE 9.6 Some Useful and Common Hydrates

Formula	Chemical Name	Common Name	Uses
$CaSO_4 \cdot H_2O$	Calcium sulfate monohydrate	Plaster of Paris	Plaster, casts, molds
$CaSO_4 \cdot 2H_2O$	Calcium sulfate dihydrate	Gypsum	Casts, molds, wallboard
$MgSO_4 \cdot 7H_2O$	Magnesium sulfate heptahydrate	Epsom salts	Cathartic
$Na_2B_4O_7 \cdot 10H_2O$	Sodium tetraborate decahydrate	Borax	Laundry
$Na_2CO_3 \cdot 10H_2O$	Sodium carbonate decahydrate	Washing soda	Water softener
$Na_3PO_4 \cdot 12H_2O$	Sodium phosphate dodecahydrate	Trisodium phosphate (TSP)	Water softener
$Na_2SO_4 \cdot 10H_2O$	Sodium sulfate decahydrate	Glauber's salt	Cathartic
$Na_2S_2O_3 \cdot 5H_2O$	Sodium thiosulfate pentahydrate	Hypo	Film photography

Many salts occur in nature, and some are used as industrial raw materials. Examples are sodium chloride, NaCl (a source of Cl_2 and NaOH); calcium carbonate or limestone, $CaCO_3$ (a source of cement and building stone); and calcium phosphate or rock phosphate, $Ca_3(PO_4)_2$ (a source of fertilizer). In the laboratory, salts can be prepared by reacting a solution of an appropriate acid with a metal, a metal oxide, a metal hydroxide, a metal carbonate, or a metal bicarbonate. These reactions, given earlier as examples of acid properties (Equations 9.19, 9.13, 9.14, 9.15, and 9.16), are given below in a general form:

$$\text{acid} + \text{metal} \rightarrow \text{salt} + H_2 \qquad (9.26)$$

$$\text{acid} + \text{metal oxide} \rightarrow \text{salt} + H_2O \qquad (9.27)$$

$$\text{acid} + \text{metal hydroxide} \rightarrow \text{salt} + H_2O \qquad (9.28)$$

$$\text{acid} + \text{metal carbonate} \rightarrow \text{salt} + H_2O + CO_2 \qquad (9.29)$$

$$\text{acid} + \text{metal bicarbonate} \rightarrow \text{salt} + H_2O + CO_2 \qquad (9.30)$$

Example 9.9 Compound Preparation Equations

Write equations to represent the preparation of $Mg(NO_3)_2$, using Reactions 9.26 through 9.30. Use molecular equations to emphasize the salt formation.

Solution

In each case, a dilute solution of nitric acid (HNO_3) is reacted with magnesium metal or the appropriate magnesium compound:

$$2HNO_3(aq) + Mg(s) \rightarrow Mg(NO_3)_2(aq) + H_2(g)$$

$$2HNO_3(aq) + MgO(s) \rightarrow Mg(NO_3)_2(aq) + H_2O(\ell)$$

$$2HNO_3(aq) + Mg(OH)_2(s) \rightarrow Mg(NO_3)_2(aq) + 2H_2O(\ell)$$

$$2HNO_3(aq) + MgCO_3(s) \rightarrow Mg(NO_3)_2(aq) + H_2O(\ell) + CO_2(g)$$

$$2HNO_3(aq) + Mg(HCO_3)_2(s) \rightarrow Mg(NO_3)_2(aq) + 2H_2O(\ell) + 2CO_2(g)$$

✔ **LEARNING CHECK 9.13** Write balanced equations to represent the preparation of $AlCl_3$, using Reactions 9.26 through 9.30. Use molecular equations to emphasize the salt formation.

equivalent of salt The amount that will produce 1 mol of positive (or negative) electric charges during dissociation when dissolved.

We have expressed the amounts of materials involved in chemical reactions primarily in terms of mass (grams) or number of moles. However, in certain applications, it is important to express the amount of salt in a solution in terms of the amount of electrical charge represented by the ions of the salt. This is especially true in medical applications, where the levels and balance of electrolytes in various body fluids are extremely important.

A unit that expresses the amount of ionic electrical charge for salts is the equivalent. One **equivalent of salt** is the amount that will produce 1 mol of positive (or negative) charges when dissolved and dissociated. To determine the amount of salt that represents 1 equivalent (eq), you must know what ions are produced when the salt dissociates. For example, potassium chloride (KCl), an electrolyte often administered to patients following surgery (see **Figure 9.15**), dissociates as follows: $KCl(aq) \rightarrow K^+(aq) + Cl^-(aq)$. Thus, 1 mol, or 74.6 g, of solid KCl provides 1 mol of positive charges (1 mol of K^+ ions) when it dissolves and dissociates. Thus, 1 eq of KCl is equal to 1 mol, or 74.6 g, of KCl.

Memory Stockphoto/Shutterstock.com

FIGURE 9.15 Potassium chloride, KCl, is used to treat low blood levels of potassium (hypokalemia).

Example 9.10 Equivalents of Salts

Potassium and calcium are two of the most important minerals in the body and are involved in numerous essential functions. Determine the number of equivalents and milliequivalents (meq) of salt contained in the following:

a. 0.050 mol KCl

b. 0.050 mol $CaCl_2$

Solution a.

STEP 1: Examine the question for what is given and what is unknown.

Given: 0.050 mol KCl

Unknown: eq KCl and meq KCl = ?

STEP 2: Identify a formula that links the given and unknown terms.

$$1 \text{ mol KCl} = 1 \text{ eq KCl}$$

Therefore,

$$0.050 \text{ mol KCl} = 0.050 \text{ eq KCl}$$

The fact that 1 eq = 1000 meq will also be used in factor form.

STEP 3: Enter the data into the formula. Use the factor-unit method to enter the data, starting with the unit eq and then employing the factor 1000 meq/1 eq to cancel the unit eq and end with meq.

$$0.050 \cancel{\text{eq}} \times \frac{1000 \text{ meq}}{1 \cancel{\text{eq}}} = 50 \text{ meq}$$

STEP 4: Check to see whether the answer makes sense.

Yes. To convert meq back to eq, move the decimal three places to the left, giving 0.050 eq.

Solution b.

STEP 1: Examine the question for what is given and what is unknown.

Given: 0.050 mol $CaCl_2$

Unknown: eq $CaCl_2$ and meq $CaCl_2$ = ?

STEP 2: Identify a formula that links the given and unknown terms. The dissociation reaction is

$$CaCl_2\,(aq) \rightarrow Ca^{2+}\,(aq) + 2Cl^-\,(aq)$$

Thus, we see that 1 mol of $CaCl_2$ produces 1 mol of Ca^{2+} or 2 mol of positive charges. Therefore, 1 mol of $CaCl_2$ = 2 eq of $CaCl_2$.

STEP 3: Enter the data into the formula. Use the factor-unit method to enter the data, starting with the unit mol $CaCl_2$ and then employing the factor

$$\frac{2 \text{ eq } CaCl_2}{1 \text{ mol } CaCl_2}$$

to cancel the unit mol and end with eq.

$$0.050 \cancel{\text{mol } CaCl_2} \times \frac{2 \text{ eq } CaCl_2}{1 \cancel{\text{mol } CaCl_2}} = 0.10 \text{ eq } CaCl_2$$

Also, because 1 eq = 1000 meq,

$$0.10 \cancel{\text{eq}} \times \frac{1000 \text{ meq}}{1 \cancel{\text{eq}}} = 1.0 \times 10^2 \text{ meq}$$

STEP 4: Check to see whether the answer makes sense.
Yes. To convert meq back to eq, move the decimal three places to the left, giving 0.10 eq.

✔ LEARNING CHECK 9.14 Determine the number of equivalents and milliequivalents in each of the following:

a. 0.10 mol NaCl
b. 0.10 mol $Mg(NO_3)_2$

Example 9.11 More Equivalent Calculations

A sample of blood serum contains 0.139 equivalents of Na^+ ion per liter of serum. Assume the Na^+ comes from dissolved NaCl, and calculate the number of equivalents, number of moles, and number of grams of NaCl in 250. mL of the serum.

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: 0.139 eq/L of Na^+ from dissolved NaCl

Unknown: moles, grams, and equivalents of NaCl in 250. mL

STEP 2 Identify a formula that links the given and unknown terms. The Na^+ has a single charge, so we may write the following relationships:

$$1.0\ \text{mol NaCl} = 1.00\ \text{mol Na}^+ = 1.00\ \text{eq Na}^+ = 1.00\ \text{eq NaCl}$$

These relationships provide numerous factors that can be used in the factor-unit method to solve problems. Two that will be used to solve these problems are

$$1.0\ \text{eq NaCl}/1.00\ \text{eq Na}^+ \qquad \text{and} \qquad 1.00\ \text{mol NaCl}/1.00\text{eq NaCl}$$

The known quantity is 250. mL of serum. This can be converted into equivalents of Na^+ by using the given concentration of 0.139 eq of Na^+/L serum as the factor.

$$(0.250\ \cancel{\text{L serum}}) \times \frac{0.139\ \text{eq of Na}^+}{1.00\ \cancel{\text{L of serum}}} = 0.0347\ \text{eq of Na}^+$$

STEP 3 Solve for eq, mol, and g of NaCl. The number of equivalents of Na^+ will now be converted into the quantities asked for by using the two factors given above and a factor obtained from the formula weight for NaCl of 58.44 u.

$$(0.0347\ \cancel{\text{eq Na}^+}) \times \frac{1.00\ \text{eq of NaCl}}{1.00\ \cancel{\text{eq of Na}^+}} = 0.0347\ \text{eq of NaCl}$$

$$(0.0347\ \cancel{\text{eq NaCl}}) \times \frac{1.00\ \text{mol of NaCl}}{1.00\ \cancel{\text{eq of NaCl}}} = 0.0347\ \text{mol of NaCl}$$

$$(0.0347\ \cancel{\text{mol NaCl}}) \times \frac{58.44\ \text{g of NaCl}}{1.00\ \cancel{\text{mol of NaCl}}} = 2.03\ \text{g of NaCl}$$

STEP 4 Check to see whether the answer makes sense.

Yes. Because 250 mL is one-fourth of a liter, the eq of NaCl should be 0.0347, one-fourth of 0.139 eq, the amount in 1 liter.

✔ LEARNING CHECK 9.15 A sample of blood serum contains 0.103 equivalents of Cl^- ions per liter. Assume the Cl^- comes from dissolved NaCl and calculate the number of equivalents, number of moles, and number of grams of NaCl in 250. mL of serum.

9.9 The Strengths of Acids and Bases

Learning Objective 9 Demonstrate an understanding of the words *weak* and *strong* as applied to acids and bases.

When salts dissolve in water, they generally dissociate completely, but this is not true for all acids and bases. The acids and bases that do dissociate almost completely are classified as **strong acids** and **strong bases** (they are also strong electrolytes). Those that dissociate to a much smaller extent are called **weak** or **moderately weak**, depending on the degree of dissociation (they are also weak or moderately weak electrolytes). Examples of strong and weak acids are given in **Table 9.7**.

strong acids and **strong bases** Acids and bases that dissociate (ionize) completely when dissolved to form a solution.

weak (or **moderately weak**) **acids** and **bases** Acids and bases that dissociate (ionize) less than completely when dissolved to form a solution.

TABLE 9.7 Some Common Strong and Weak Acids

Name	Formula	% Dissociation[a]	K_a	Classification
Hydrochloric acid	HCl	100	Very large	Strong
Hydrobromic acid	HBr	100	Very large	Strong
Nitric acid	HNO_3	100	Very large	Strong
Sulfuric acid	H_2SO_4	100	Very large	Strong
Phosphoric acid	H_3PO_4	28	7.5×10^{-3}	Moderately weak
Sulfurous acid[b]	H_2SO_3	34	1.5×10^{-2}	Moderately weak
Acetic acid	$HC_2H_3O_2$	1.3	1.8×10^{-5}	Weak
Boric acid	H_3BO_3	0.01	7.3×10^{-10}	Weak
Carbonic acid[b]	H_2CO_3	0.2	4.3×10^{-7}	Weak
Nitrous acid[b]	HNO_2	6.7	4.6×10^{-4}	Weak

[a] Based on dissociation of one proton in 0.1 M solution at 25°C.

[b] Unstable acid.

A 0.10 M solution of hydrochloric acid could be prepared by dissolving 0.10 mol (3.7 g) of HCl gas in enough water to give 1.0 L of solution. According to **Table 9.7**, 100% of the dissolved gas would dissociate into H^+ and Cl^-. Thus, the concentration of H^+ in a 0.10 M HCl solution is 0.10 mol/L, and the pH is 1.00.

The strength of acids and bases is shown quantitatively by the value of the equilibrium constant for the dissociation reaction in water solutions. Equation 9.31 represents the dissociation of a general acid, HB, in water, where B^- represents the conjugate base of the acid:

$$HB(aq) + H_2O(\ell) \rightleftarrows H_3O^+(aq) + B^-(aq) \tag{9.31}$$

The equilibrium expression for this reaction is

$$K = \frac{[H_3O^+][B^-]}{[HB][H_2O]} \tag{9.32}$$

In Equation 9.32, the brackets, again, represent molar concentrations of the materials in the solution. Only a tiny amount of the water in the solution actually enters into the reaction, so the concentration of water is considered to be constant (see **Section 9.4**). We can then write Equation 9.33, where K_a is a new constant called the **acid dissociation constant**:

acid dissociation constant The equilibrium constant for the dissociation of an acid.

$$K[H_2O] = K_a = \frac{[H_3O^+][B^-]}{[HB]} \tag{9.33}$$

In Equation 9.33, $[H_3O^+]$ and $[B^-]$ are, respectively, the equilibrium concentrations of the hydronium ion and the anion conjugate base that is characteristic of the acid. The [HB] represents the concentration of that part of the dissolved acid that remains undissociated in the equilibrium mixture. In solutions of strong acids, $[H_3O^+]$ and $[B^-]$ values are quite large, while [HB] has a value near 0, so K_a is quite large. In weak acids, [HB] has larger values, while $[H_3O^+]$ and $[B^-]$ are smaller, so K_a is smaller. Thus, the larger a K_a value, the stronger the acid it represents. This is illustrated by the K_a values given in **Table 9.7**. If we simplify by substituting H^+ for H_3O^+, we obtain

$$K_a = \frac{[H^+][B^-]}{[HB]} \tag{9.34}$$

It is important to remember that the terms *weak* and *strong* apply to the extent of dissociation and not to the concentration of an acid or base. For example, gastric juice (0.05% HCl) is a dilute (not weak) solution of a strong acid.

Example 9.12 Dissociation Reactions of Acids

Write dissociation reactions and expressions for K_a for each of the following weak acids:

a. Hydrocyanic acid (HCN)
b. Phosphoric acid (H_3PO_4) (1st H only)
c. Dihydrogen phosphate ion ($H_2PO_4^-$) (1st H only)

Solution

In each case, H^+ has been substituted for H_3O^+.

a. $HCN \leftrightarrows H^+ + CN^-; \quad K_a = \frac{[H^+][CN^-]}{[HCN]}$

b. $H_3PO_4 \leftrightarrows H^+ + H_2PO_4^-; \quad K_a = \frac{[H^+][H_2PO_4^-]}{[H_3PO_4]}$

c. $H_2PO_4^- \leftrightarrows H^+ + HPO_4^{2-}; \quad K_a = \frac{[H^+][HPO_4^{2-}]}{[H_2PO_4^-]}$

✔ **LEARNING CHECK 9.16** Write dissociation reactions and K_a expressions for the following weak acids:

a. Hydrogen phosphate ion (HPO_4^{2-})
b. Nitrous acid (HNO_2)
c. Hydrofluoric acid (HF)

FEEDS 5,000 SQ. FT.
NET WT. 15 LBS.
Glorion
Deluxe
FALL FERTILIZER
10-18-10
GUARANTEED ANALYSIS
GLORION CORPORATION

Diane Hirsch/Fundamental Photographs

FIGURE 9.16 Phosphoric acid, H_3PO_4, is used to make phosphate salts for fertilizers. It is also used in dental cements.

Acid behavior is linked to the loss of protons. Thus, acids must contain hydrogen atoms that can be removed to form H^+. **Monoprotic acids** can lose only one proton per molecule, whereas **diprotic** and **triprotic** acids can lose two and three, respectively. For example, HCl is monoprotic, H_2SO_4 is diprotic, and H_3PO_4 is triprotic (see **Figure 9.16**). Diprotic and triprotic acids dissociate in steps, as shown for H_2SO_4 in Equations 9.35 and 9.36:

$$H_2SO_4(aq) \rightleftarrows H^+(aq) + HSO_4^-(aq) \tag{9.35}$$

$$HSO_4^-(aq) \leftrightarrows H^+(aq) + SO_4^{2-}(aq) \tag{9.36}$$

The second proton is not as easily removed as the first because it must be pulled away from a negatively charged particle, HSO_4^-. Accordingly, HSO_4^- is a weaker acid than H_2SO_4.

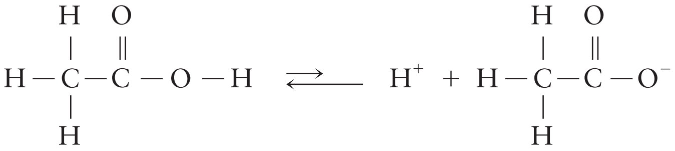
The number of ionizable hydrogens cannot always be determined from the molecular formula for an acid. For example, acetic acid ($HC_2H_3O_2$) is monoprotic even though the molecule contains four hydrogen atoms. The dissociation of acetic acid is represented by

monoprotic acid An acid that gives up only one proton (H^+) per molecule when dissolved.

diprotic acid An acid that gives up two protons (H^+) per molecule when dissolved.

triprotic acid An acid that gives up three protons (H^+) per molecule when dissolved.

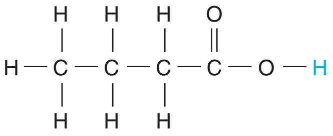
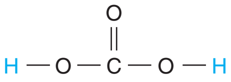
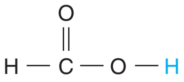
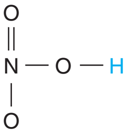
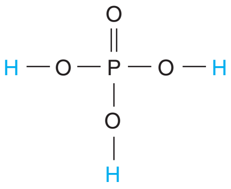
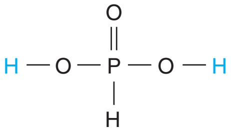
Equation 9.37, where structural formulas are used to emphasize the different H atoms in the molecule:



$$\mathrm{H{-}\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}{-}\overset{\overset{O}{\|}}{C}{-}O{-}H \rightleftharpoons H^{+} + H{-}\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}{-}\overset{\overset{O}{\|}}{C}{-}O^{-}} \qquad (9.37)$$

Only the hydrogen bound to the oxygen is ionizable. Those hydrogens bound to C are too tightly held to be removed. **Table 9.8** contains other examples, with the ionizable hydrogens shown in color.

TABLE 9.8 **Examples of Monoprotic, Diprotic, and Triprotic Acids**

Name	Formula	Structural Formula	Classification
Butyric acid	$HC_4H_7O_2$	 $\mathrm{H{-}\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}{-}\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}{-}\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{C}}{-}\overset{\overset{O}{\|}}{C}{-}O{-}H}$	Monoprotic
Carbonic acid	H_2CO_3	 $\mathrm{H{-}O{-}\overset{\overset{O}{\|}}{C}{-}O{-}H}$	Diprotic
Formic acid	$HCHO_2$	 $\mathrm{H{-}\overset{\overset{O}{\|}}{C}{-}O{-}H}$	Monoprotic
Nitric acid	HNO_3	 $\mathrm{\underset{\underset{O}{|}}{\overset{\overset{O}{\|}}{N}}{-}O{-}H}$	Monoprotic
Phosphoric acid	H_3PO_4	 $\mathrm{H{-}O{-}\underset{\underset{\underset{\underset{H}{|}}{O}}{|}}{\overset{\overset{O}{\|}}{P}}{-}O{-}H}$	Triprotic
Phosphorous acid	H_3PO_3	 $\mathrm{H{-}O{-}\underset{\underset{H}{|}}{\overset{\overset{O}{\|}}{P}}{-}O{-}H}$	Diprotic

We have focused our attention on the strength of acids, using the extent of dissociation as a basis. However, all acid dissociations are reversible to some degree, and in the reverse reactions, anions produced by the forward reaction behave as Brønsted bases. What can be said about the strength of these bases? Because Brønsted acid–base behavior is really just competition for protons, we can answer this question by looking again at the simplified form of the equation for dissociation of a general acid:

$$HB(aq) \leftrightarrows H^{+}(aq) + B^{-}(aq) \qquad (9.38)$$

We see from this equation that the strength of HB as an acid depends on how tightly the conjugate base B^{-} holds onto the proton. If HB is a strong acid, the conjugate base holds onto the proton only weakly. If HB is a weak acid, the conjugate base holds on more

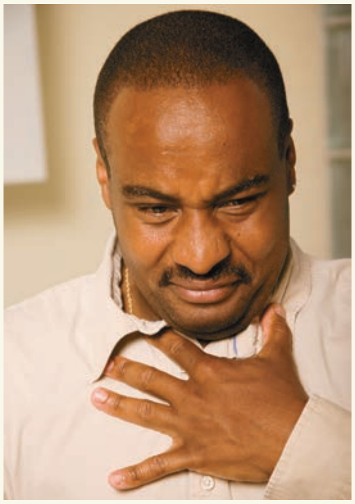
HEALTH CONNECTIONS 9.1

Heartburn Alert

The medical name for acid reflux disease is *gastroesophageal reflux disease,* which is often abbreviated and referred to as GERD. The disease is often mistaken for occasional heartburn and treated with over-the-counter remedies. GERD is the result of a malfunctioning muscle (the lower esophageal sphincter [LES] muscle) located at the bottom of the esophagus, just above the stomach. When operating normally, this muscle relaxes and opens to allow food to pass from the esophagus down into the stomach, then contracts to close the opening and prevent the acidic contents of the stomach from backing up into the esophagus.

Doctors often recommend lifestyle and dietary changes for most GERD patients, including the avoidance of foods and beverages that weaken the LES muscle. These foods include chocolate, peppermint, fatty foods, coffee, and alcoholic beverages. The use of foods and beverages that can irritate a damaged esophageal lining, such as acidic fruits and juices, pepper, and tomato products is also discouraged. GERD symptoms in overweight individuals often diminish when some weight is lost. Smokers who quit also generally gain some relief. Prescription medications that reduce the amount of acid in the stomach are also available. Two types of medication are available. Both types, called H2 blockers and proton (acid) pump inhibitors, decrease the amount of acid secreted into the stomach, but by different mechanisms.

The main symptom that may indicate the presence of GERD is frequent, persistent heartburn that occurs two or more times a week. Other symptoms include difficulty in swallowing and frequent belching and regurgitation. Individuals who suspect they might be suffering from some degree of GERD should consult a physician to determine the extent of the disease and proper treatment.



Custom Medical Stock Photo/Alamy Stock Photo

GERD has many degrees of severity.

strongly, depending on the strength of HB. Thus, we have answered our earlier question. If HB is a strong acid, the H^+ is held only weakly by the B^-. We can conclude then that B^- is not strongly attracted to protons—it is a weak base. Conversely, if HB is a weak acid, the H^+ is held tightly by the B^-, and we conclude that B^- is more strongly attracted to protons—it is a stronger base than the B^- from a strong acid.

In general, the conjugate base anions produced by the dissociation of strong Brønsted acids are weak Brønsted bases. The conjugate base anions of weak acids are stronger bases, with their strengths dependent on the strength of the parent acid.

Ammonia (NH_3) is the weak base most often encountered in addition to the anions of strong acids. The dissociation reaction of gaseous NH_3 in water, given earlier in Example 9.1, is

$$NH_3(aq) + H_2O(\ell) \rightleftarrows NH_4^+(aq) + OH^-(aq) \qquad (9.39)$$

The most common strong bases are the hydroxides of group IA(1) metals (NaOH, KOH, etc.) and the hydroxides of group IIA(2) metals ($Mg(OH)_2$, $Ca(OH)_2$, etc.).

Example 9.13 Strengths of Acids

Classify each of the following pairs by identifying the stronger of the pair according to the indicated behavior. Information from **Tables 9.7** and **9.8** may be used.

a. H_3PO_4 and $H_2PO_4^-$ (acid)
b. $H_2PO_4^-$ and HPO_4^{2-} (base)
c. HNO_3 and HNO_2 (acid)

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Solution

a. H_3PO_4 is stronger as an acid. In diprotic and triprotic acids, each proton in the removal sequence is harder to remove, so the corresponding acid is weaker.

b. The stronger acid produces the weaker anion base. Thus, $H_2PO_4^-$, the anion of the stronger acid H_3PO_4, would be a weaker base than HPO_4^{2-}, the anion of the weaker acid $H_2PO_4^-$. So HPO_4^{2-} is a stronger base than $H_2PO_4^-$.

c. HNO_3 is the stronger acid according to **Table 9.7**. Generally, when related acids (same atoms, etc.) are compared for strength, the one containing more oxygen atoms will be the stronger.

✔ **LEARNING CHECK 9.17** Classify each of the following according to strength for the indicated behavior. If more than two are compared, list them with the strongest at the top and the weakest at the bottom. Use **Tables 9.7** and **9.8** as needed.

a. $HClO$, $HClO_3$, $HClO_2$ (acid)
b. NO_2^- and NO_3^- (base)
c. $HC_2H_3O_2$ and $C_2H_3O_2^-$ (acid)

9.10 Analyzing Acids and Bases

Learning Objective 10 Demonstrate an understanding of the titration technique used to analyze acids and bases.

The analysis of solutions for the total amount of acid or base they contain is a regular activity in many laboratories. The total amount of acid in a solution is indicated by its capacity to neutralize a base. The pH is related to the acidity or concentration of H^+ in solution, while the capacity to neutralize a base depends on the total amount of H^+ available. For example, a 0.10 M acetic acid solution has an H^+ concentration of about 1.3×10^{-3} M (pH = 2.89). However, 1 L of the solution can neutralize 0.10 mol of OH^-, not just 1.3×10^{-3} mol. The reason is that the dissociation equilibrium of acetic acid is

$$HC_2H_3O_2(aq) \rightleftarrows H^+(aq) + C_2H_3O_2^-(aq) \qquad (9.40)$$

As OH^- is added, H^+ reacts to form water (see Equation 9.24). The removal of H^+ causes the equilibrium of Reaction 9.40 to shift right in accordance with Le Châtelier's principle. The continuous addition of OH^- and removal of H^+ will eventually cause all of the acetic acid molecules to dissociate and react.

A common procedure often used to analyze acids and bases is called **titration** (see **Figure 9.17**). Suppose the acidity of an unknown acid solution needs to be determined. A known volume of the acidic solution is first measured out by drawing it up to the calibration mark of a pipet. This solution is placed in a container (Step 1). A basic solution of known concentration (a standard solution) is added to the acid solution in the container until the **equivalence point of a titration** is reached. This is the point where the unknown acid is completely reacted with base. The volume of base needed to reach the equivalence point is obtained from the buret readings.

titration An analytical procedure in which one solution (often a base) of known concentration is slowly added to a measured volume of an unknown solution (often an acid). The volume of the added solution is measured with a buret.

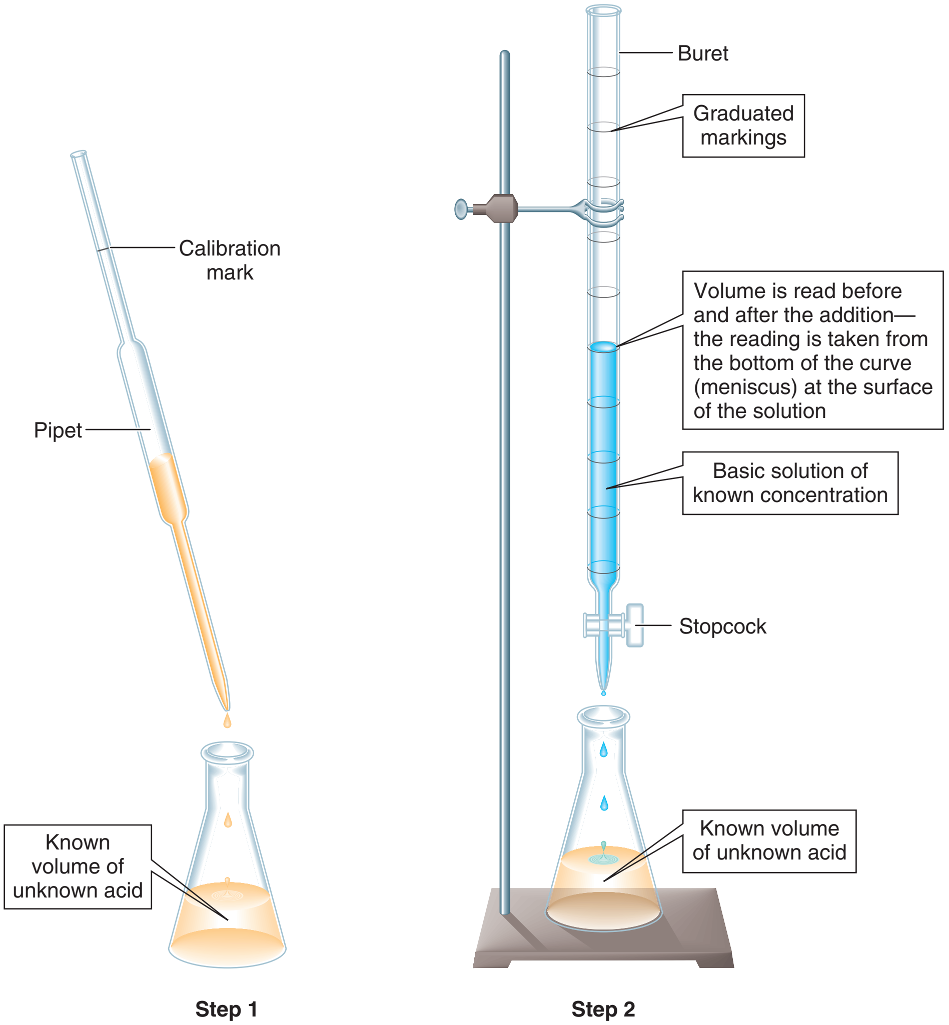
equivalence point of a titration The point at which the unknown solution has exactly reacted with the known solution. Neither is in excess.

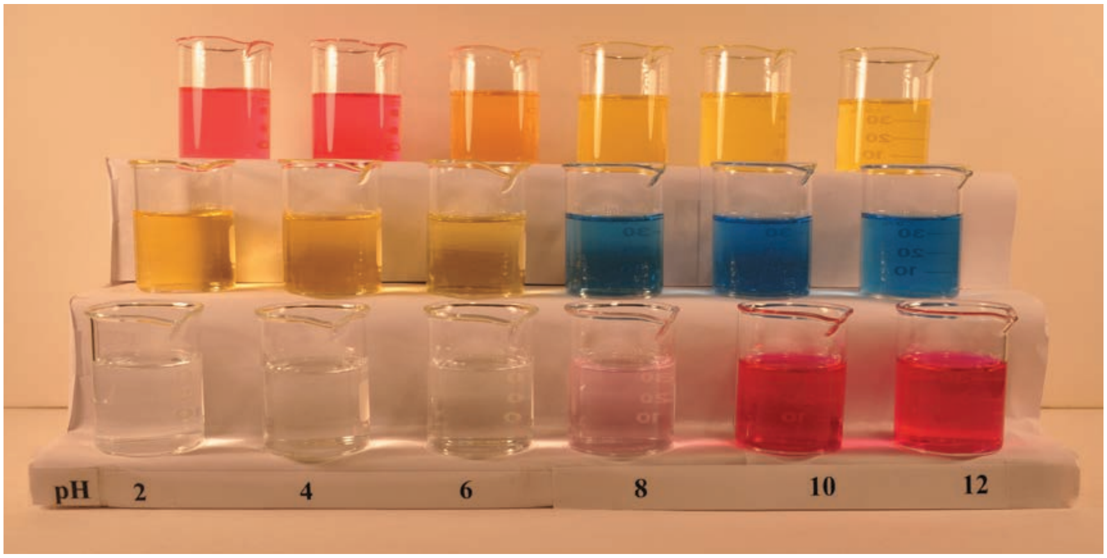
To successfully complete a titration, the point at which the reaction is completed must somehow be detected. One way to do this is to add an indicator to the solution being titrated. An indicator is an organic compound that changes to different colors depending on the pH of its surroundings. An indicator is selected that will change color at a pH as close as possible to the pH the solution will have at the equivalence point. If the acid and base are both strong, the pH at that point will be 7. However, for reasons discussed later, the pH is not always 7 at the equivalence point. The point at which the indicator changes color and the titration is stopped is called the **endpoint of a titration. Figure 9.18** gives the colors shown by a number of indicators at various pH values.

endpoint of a titration The point at which the titration is stopped on the basis of an indicator color change or pH meter reading.

Indicator papers (litmus paper, pH paper, etc.) are often used to make routine pH measurements. These papers are impregnated with one or more indicators that change to

FIGURE 9.17 Titration.


Buret
Graduated markings
Calibration mark
Volume is read before and after the addition—the reading is taken from the bottom of the curve (meniscus) at the surface of the solution
Pipet
Basic solution of known concentration
Stopcock
Known volume of unknown acid
Known volume of unknown acid
Step 1
Step 2


pH
2
4
6
8
10
12

© Jeffrey M. Seager

FIGURE 9.18 Indicators change color with changes in pH (the numbers across the bottom). Methyl red (top row) goes from red at low pH to yellow at higher pH. Bromothymol blue (middle row) goes from yellow to blue, and phenolphthalein (bottom row) goes from colorless to red. Which of the three indicators would be the best to use to differentiate between the solutions with pH values of 4 and 6?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

a variety of colors depending on the pH. However, indicators may not be practical under certain conditions. For example, there might not be any indicator that changes color close enough to the equivalence point, or the solution being titrated might be so highly colored that an indicator color change cannot be detected. Under such circumstances, a pH meter can be used. The electrodes of the meter are placed in the solution being titrated, and the pH is read directly (see **Figure 9.19**). The titration is continued until the meter reading matches the pH of the equivalence point.

© Spencer L. Seager

a At the beginning, the pH meter gives the pH of the acid solution being titrated.

© Spencer L. Seager

b Partway through the titration, the pH meter reading is of a solution of unreacted acid and the salt produced by the reaction.

© Spencer L. Seager

c At the end of the titration, the pH meter gives the pH of the salt solution formed by the complete reaction of acid with base.

FIGURE 9.19 An acid–base titration using a pH meter to detect the equivalence point.

9.11 Titration Calculations

Learning Objective 11 Do calculations related to the analysis of acids and bases by titration.

Equations 9.41 and 9.42 represent the reactions that occur when solutions of nitric and sulfuric acid are titrated with sodium hydroxide:

$$HNO_3(aq) + NaOH(aq) \rightarrow NaNO_3(aq) + H_2O(\ell) \tag{9.41}$$

$$H_2SO_4(aq) + 2NaOH(aq) \rightarrow Na_2SO_4(aq) + 2H_2O(\ell) \tag{9.42}$$

One mole of HNO_3 requires 1 mol of NaOH for a complete reaction, but 1 mol of H_2SO_4 requires 2 mol of NaOH. Because these are solution reactions, stoichiometric calculations can be done using the methods described in **Section 7.6**.

Example 9.14 Titration Calculations

A 25.0 mL sample of an HNO_3 solution requires the addition of 16.3 mL of 0.200 M NaOH to reach the equivalence point. Calculate the molarity of the HNO_3 solution.

The equation for the reaction is

$$HNO_3\ (aq) + NaOH\ (aq) \rightarrow NaNO_3\ (aq) + H_2O\ (\ell)$$

Solution

STEP 1 Examine the equation for what is given and what is unknown.

Given: 25.0 mL of HNO_3 reacts with 16.3 mL of 0.200 M NaOH   Unknown: M of HNO_3 = ?

STEP 2 Identify a formula that links the given and unknown terms. We know the volume of acid solution reacted. If we also knew the number of moles of acid in the volume of reacted solution, we could calculate the solution molarity by using Key Equation 7.5:

$$M = \frac{\text{moles of solute}}{\text{liters of solution}}$$

Therefore, our task will be to calculate the number of moles of acid reacted. The equation for the reaction shows that 1 mol of HNO_3 requires 1 mol of NaOH. Thus, by calculating the moles of NaOH, we know the moles of HNO_3 reacted.

STEP 3 Calculate the moles of NaOH, using the factor-unit method.

a. $$16.3\ \cancel{\text{mL}}\ \text{NaOH solution} \times \frac{1\ \text{L}}{1000\ \cancel{\text{mL}}} = 0.0163\ \text{L NaOH solution}$$

b. $$0.0163\ \cancel{\text{L NaOH}} \times \frac{0.200\ \text{mol NaOH}}{1\ \cancel{\text{L NaOH}}} = 0.00326\ \text{mol NaOH}$$

Because moles of NaOH = moles of HNO_3, we get moles of $HNO_3 = 0.00326$

STEP 4 Calculate the molarity of HNO_3. After converting the HNO_3 volume to liters, the molarity can be calculated.

$$25.0\ \cancel{\text{mL}}\ HNO_3\ \text{solution} \times \frac{1\ \text{L}}{1000\ \cancel{\text{mL}}} = 0.0250\ \text{L}\ HNO_3\ \text{solution}$$

M = moles of HNO_3 solution/liters of HNO_3 solution = 0.00326 mol HNO_3/0.0250 L HNO_3 = 0.130 mol HNO_3/L HNO_3 solution = 0.130 M HNO_3

STEP 5 Check to see whether the answer makes sense.

Yes. The reaction required more HNO_3 to react with the NaOH, so we would expect the concentration of HNO_3 to be a little less than the concentration of NaOH.

✔ **LEARNING CHECK 9.18** Calculate the molarity of a solution of phosphoric acid (H_3PO_4) if a 25.0 mL sample of acid solution requires 14.1 mL of a 0.250 M NaOH solution to titrate to the equivalence point. The equation for the reaction is

$$H_3PO_4(aq) + 3NaOH(aq) \rightarrow Na_3PO_4(aq) + 3H_2O(aq)$$

9.12 Hydrolysis Reactions of Salts

Learning Objective 12 Explain the concept of salt hydrolysis, and write equations to illustrate the concept.

hydrolysis reaction Any reaction with water. For salts, it is a reaction of the acidic cation and/or basic anion of the salt with water.

In general, a **hydrolysis reaction** is a reaction with water. Many types of hydrolysis reactions are known, but at this point we will discuss only one, the hydrolysis of salts. In **Section 9.10**, we said that the pH at the equivalence point is not 7 for all acid–base titrations. However, we pointed out earlier that the only products of acid–base reactions are water and a salt. Therefore, it seems reasonable to conclude that some salts and water must interact (a hydrolysis reaction) and cause the solution pH to differ from that of pure water.

Suppose three solutions are prepared by dissolving equal molar amounts of sodium acetate, ammonium chloride, and sodium chloride in identical volumes of pure water. Measurement of pH shows that the sodium acetate solution is alkaline (pH higher than 7), the ammonium chloride solution is acidic (pH lower than 7), and the sodium chloride solution is neutral (pH = 7). The alkaline sodium acetate solution must contain more OH^- than H^+ ions. However, the only source of both ions in a solution of salt and water is the dissociation of water, so both should be present in equal amounts. The equation for the water dissociation is

$$H_2O(\ell) \rightleftarrows H^+(aq) + OH^-(aq) \tag{9.43}$$

The OH^- excess would result if something removed H^+ from this equilibrium, causing it to shift right and produce more OH^-. This is exactly what happens. The acetate anion is the conjugate base of a weak acid (acetic acid), and it is a strong enough Brønsted base to react with the H^+ ions of the above equilibrium:

$$C_2H_3O_2^-(aq) + H^+(aq) \rightleftarrows HC_2H_3O_2(aq) \tag{9.44}$$

The overall result of this reaction can be seen by adding Equations 9.43 and 9.44:

$$H_2O(\ell) + C_2H_3O_2^-(aq) + H^+(aq) \rightleftarrows H^+(aq) + OH^-(aq) + HC_2H_3O_2(aq) \tag{9.45}$$

$$\text{Net reaction: } H_2O(\ell) + C_2H_3O_2^-(aq) \rightleftarrows OH^-(aq) + HC_2H_3O_2^-(aq) \tag{9.46}$$

Now it can be seen that the excess OH^- comes from a reaction between the acetate ion and water. But what about the Na^+ ion that is also in the solution? Does it react with water? The Na^+ cation is the conjugate acid of the strong base NaOH. As a result, Na^+ is an extremely weak Brønsted acid and makes no contribution to the pH of the solution.

In general, salts influence the pH of water solutions as follows: (1) Salts containing an anion of a weak acid and a cation of a strong base will form alkaline water solutions. (2) Salts containing an anion of a strong acid and a cation of a weak base will form acidic solutions. (3) Salts containing an anion and a cation from equal-strength acids and bases (both weak or both strong) will form neutral solutions (see **Figure 9.20**).

The acidic ammonium chloride solution is an example of the second category of salts, where the NH_4^+ cation is the conjugate acid of the weak base NH_3, and the Cl^- anion is the conjugate base of the strong acid HCl. The hydrolysis reaction is given in Equation 9.47, where H_3O^+ is used to emphasize the reaction with water:

$$NH_4^+(aq) + H_2O(\ell) \rightleftarrows H_3O^+(aq) + NH_3(aq) \qquad (9.47)$$

The neutral sodium chloride solution is an example of the third category. Both NaOH and HCl are strong, and an NaCl solution is neutral.

✔ **LEARNING CHECK 9.19** Predict the relative pH value (higher than 7, lower than 7, etc.) for water solutions of the following salts. **Table 9.7** may be useful.

a. Sodium nitrate ($NaNO_3$)
b. Sodium nitrite ($NaNO_2$)
c. Potassium borate (K_3BO_3)

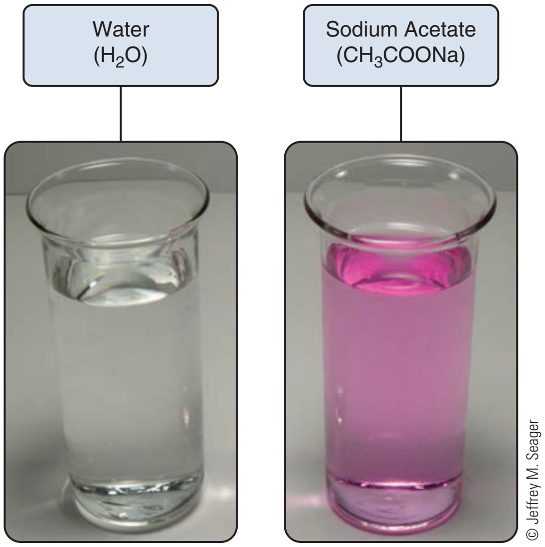


FIGURE 9.20 Samples of pure water (left) and sodium acetate dissolved in water (right) behave differently when phenolphthalein indicator is added. The acetate ion hydrolyzes in water to form a basic solution that turns phenolphthalein to a pink color. Why didn't the Na^+ ion from the sodium acetate hydrolyze?

9.13 Buffers

Learning Objective 13 Explain how buffers work, and write equations to illustrate their action.

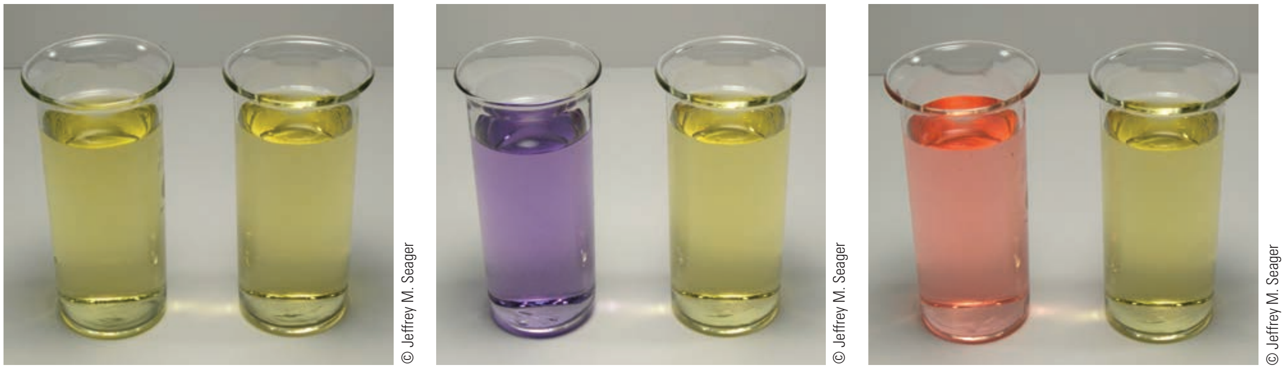
buffer A solution with the ability to resist changing pH when acids (H^+) or bases (OH^-) are added.

A **buffer** is a solution that has the ability to resist changes in pH when acids or bases are added (see **Figure 9.21**). Most buffers consist of a pair of compounds, one with the ability to react with H^+ and the other with the ability to react with OH^-. An example is a mixture of acetic acid and its salt, sodium acetate. The acetate ion from sodium acetate is the conjugate base of acetic acid and reacts with any added acid (H^+ ions):

$$C_2H_3O_2^-(aq) + H^+(aq) \rightleftarrows HC_2H_3O_2(aq) \qquad (9.48)$$

Any added base (OH^- ions) reacts with nonionized acetic acid molecules:

$$HC_2H_3O_2(aq) + OH^-(aq) \rightleftarrows C_2H_3O_2^-(aq) + H_2O(\ell) \qquad (9.49)$$


© Jeffrey M. Seager

© Jeffrey M. Seager

© Jeffrey M. Seager

a The solution on the left is not buffered; the one on the right is; universal indicator has been added to each solution.

b Sodium hydroxide has been added to each solution.

c Hydrochloric acid has been added to two fresh samples that originally looked like the first pair of samples.

FIGURE 9.21 Buffered solutions resist changing pH when bases and acids are added. What observation of this experiment indicates that the pH of the buffered solutions did not change significantly when base or acid was added?

In this way, the buffer solution resists changes in pH. The amount of H^+ or OH^- that a buffer system can absorb without allowing significant pH changes to occur is called its **buffer capacity**.

buffer capacity The amount of acid (H^+) or base (OH^-) that can be absorbed by a buffer without causing a significant change in pH.

Buffered solutions are found extensively in the body, where they serve to protect us from the disastrous effects of large deviations in pH (see **Figure 9.22**). An important buffer system in blood is composed of carbonic acid (H_2CO_3) and bicarbonate salts such as $NaHCO_3$. The unstable carbonic acid results in when dissolved CO_2 reacts with water in the blood:

$$H_2O(\ell) + CO_2(aq) \leftrightarrows H_2CO_3(aq) \tag{9.50}$$

Added H^+ is neutralized by reacting with HCO_3^- from the dissolved bicarbonate salts:

$$HCO_3^-(aq) + H^+(aq) \rightleftarrows H_2CO_3(aq) \tag{9.51}$$

The carbonic acid protects against added OH^-:

$$H_2CO_3(aq) + OH^-(aq) \leftrightarrows HCO_3^-(aq) + H_2O(\ell) \tag{9.52}$$

kotina/iStock Editorial/Getty Images

FIGURE 9.22 Blood buffers enable the body to maintain normal blood pH levels under a range of human activities.

If large amounts of H^+ or OH^- are added to a buffer, the buffer capacity can be exceeded, the buffer system is overwhelmed, and the pH changes. For example, if large amounts of H^+ were added to the bicarbonate ion–carbonic acid buffer, Reaction 9.51 would take place until the HCO_3^- was depleted. The pH would then drop as additional H^+ ions were added. In blood, the concentration of HCO_3^- is ten times the concentration of H_2CO_3. Thus, this buffer has a greater capacity against added acid than against bases. This is consistent with the normal functions of the body that cause larger amounts of acidic than basic substances to enter the blood.

The pH of buffers can be calculated by using a form of Equation 9.34 that was given earlier and is repeated here:

$$K_a = \frac{[H^+][B^-]}{[HB]}$$

This equation can be rearranged to give

$$[H^+] = K_a\frac{[HB]}{[B^-]} \tag{9.53}$$

Application of the logarithm concept to Equation 9.53 gives

$$pH = pK_a + \log\frac{[B^-]}{[HB]} \tag{9.54}$$

In this equation, pH = $-\log[H^+]$ (Equation 9.11), and **pK_a** = $-\log K_a$. Equation 9.54 is known as the **Henderson–Hasselbalch equation**; it is often used by biologists, biochemists, and others who frequently work with buffers. We see from Equation 9.54 that when the concentrations of a weak acid and its conjugate base (anion) are equal in a solution, the pH of the solution is equal to pK_a. When it is desired to produce a buffer with a pH different from the exact pK_a, Equation 9.54 indicates it can be done. An acid with a pK_a near the desired pH is selected, and the ratio of the concentrations of conjugate base (anion of the acid) and acid is adjusted to give the desired pH. When a weak acid and its salt (the source of the acid's conjugate base anion) are mixed in solution, you can generally assume that the amount of acid that dissociates is small and may be neglected. This means that the buffer concentrations of the acid and anion (the salt of acid) are "equal" to the made-up concentrations. **Table 9.9** lists some weak acids, together with values of K_a and pK_a.

pK_a The negative logarithm of K_a.

Henderson–Hasselbalch equation A relationship between the pH of a buffer, pK_a, and the concentrations of acid and salt in the buffer.

TABLE 9.9 K_a and pK_a Values for Selected Weak Acids

Name	Formula	K_a	pK_a
Acetic acid[a]	CH_3COOH	1.8×10^{-5}	4.74
Ammonium ion	NH_4^+	5.6×10^{-10}	9.25
Boric acid	H_3BO_3	7.3×10^{-10}	9.14
Dihydrogen borate ion	$H_2BO_3^-$	1.8×10^{-13}	12.75
Hydrogen borate ion	HBO_3^{2-}	1.6×10^{-14}	13.80
Carbonic acid	H_2CO_3	4.3×10^{-7}	6.37
Bicarbonate ion	HCO_3^-	5.6×10^{-11}	10.25
Citric acid[a]	$C_3H_4(OH)(COOH)_3$	8.4×10^{-4}	3.08
Dihydrogen citrate ion[a]	$C_3H_4(OH)(COOH)_2COO^-$	1.8×10^{-5}	4.74
Hydrogen citrate ion[a]	$C_3H_4(OH)(COOH)(COO)_2^{2-}$	4.0×10^{-6}	5.40
Formic acid[a]	$HCOOH$	1.8×10^{-4}	3.74
Lactic acid[a]	$C_2H_4(OH)COOH$	1.4×10^{-4}	3.85
Nitrous acid	HNO_2	4.6×10^{-4}	3.33
Phosphoric acid	H_3PO_4	7.5×10^{-3}	2.12
Dihydrogen phosphate ion	$H_2PO_4^-$	6.2×10^{-8}	7.21
Hydrogen phosphate ion	HPO_4^{2-}	2.2×10^{-13}	12.66
Sulfurous acid	H_2SO_3	1.5×10^{-2}	1.82
Bisulfite ion	HSO_3^-	1.0×10^{-7}	7.00

[a] The hydrogen that ionizes in organic acids and ions is a part of a carboxylic acid group, represented by COOH.

Example 9.15 Buffer Solution Calculations

A buffer system consisting of the ions $H_2PO_4^-$ and HPO_4^{2-} helps to control the pH of urine. What is the pH of a buffer in which the concentration of NaH_2PO_4 is 0.10 M and that of Na_2HPO_4 is 0.50 M? The pKa for $H_2PO_4^-$ is 7.21.

Solution

STEP 1 Examine the question for what is given and what is unknown.

Given: $[NaH_2PO_4] = 0.10$ M and $[Na_2HPO_4] = 0.50$ M Unknown: pH = ?

STEP 2 Identify a formula that links the given and unknown terms.

Both compounds are salts that produce the $H_2PO_4^-$ and HPO_4^{2-} ions. In such situations, the ion with more hydrogens will be the acid, and the one with fewer will be the anion or

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

conjugate base. Therefore, the acid is $H_2PO_4^-$ and the conjugate base or anion is HPO_4^{2-}. Key Equation 9.54 links the given and unknown terms.

$$\mathrm{pH} = \mathrm{pK_a} + \log\frac{[\mathrm{B}^-]}{[\mathrm{HB}]} \quad \text{or} \quad \mathrm{pH} = \mathrm{pK_a} + \log\frac{[\mathrm{HPO_4}^{2-}]}{[\mathrm{H_2PO_4^-}]}$$

STEP 3 Enter the data into the formula.

$$\mathrm{pH} = 7.21 + \log\left[\frac{0.50\ \cancel{\mathrm{mol/L}}}{0.10\ \cancel{\mathrm{mol/L}}}\right] = 7.21 + \log(5.0)$$

Use a calculator: 5.0(log) = 0.70

$$\mathrm{pH} = 7.21 + \log(5.0)$$
$$\mathrm{pH} = 7.21 + 0.70\ [\text{where } \log(5.0) = 0.70]$$
$$\mathrm{pH} = 7.91$$

STEP 4 Check to see if the answer makes sense.

Yes. The answer is a little greater than 7.21, the major contributor to the value of the pH.

✔ LEARNING CHECK 9.20

a. What is the pH of a buffer solution in which formic acid (HCOOH) and sodium formate (HCOONa) are both at a concentration of 0.22 M?
b. What is the pH of a buffer solution that is 0.25 M in sulfurous acid (H_2SO_3) and 0.10 M in sodium bisulfite ($NaHSO_3$)?
c. A buffer system in the blood consists of the bicarbonate ion, HCO_3^-, and carbonic acid, H_2CO_3. What value of the ratio $[HCO_3^-]/[H_2CO_3]$ would be required to maintain blood at the average normal pH of 7.40?

Health Career Description

RESPIRATORY THERAPIST

Respiratory therapists (RTs) have the responsibility and ability to keep patients breathing freely. RTs ensure patient health with an emphasis on breathing in a variety of settings, such as hospitals, care facilities, sleep centers, and hospice services. They participate in diagnosis of disease, interviewing and conducting physical chest exams of patients, consulting with physicians and other health care personnel, and administering medications that enhance breathing such as albuterol or steroid medications, often referred to as "breathing treatments" via nebulizers, and other medication routes.

RTs are responsible for managing the airway of patients who cannot breathe on their own. They provide airways in a variety of ways: RTs might "bag a patient," squeezing an apparatus that forces air into the lungs or intubate or use manual maneuvers to maintain a patent airway. They analyze breath, blood, and tissue samples to diagnose, manage, and treat disease. They are expected to respond to emergency and urgent care calls as well as high-risk births. RTs have knowledge in a wide range of subjects, including anatomy, physiology, chemistry, mathematics, medical terminology, and communication skills.

RTs deal with any condition that may impact breathing, such as asthma, allergies, sleep apnea, acute and chronic illness, and trauma. They are often involved in providing community education on subjects such as smoking or air-quality issues.

In order to become a respiratory therapist, students must be accepted into an accredited respiratory therapy program. An associate's degree in health professions or in respiratory therapy with a GPA above 3.5 is helpful in gaining acceptance to a program. RT programs are demanding. One such program at Weber State University in Ogden, Utah, requires students to take 20 credit hours per semester, and working outside of the program is discouraged. After completion of the program, students will hold a bachelor's degree, but must also pass a state licensing exam in order to practice. Master's degrees in respiratory therapy are also available and equip students to deal with special populations such as neonatal, pediatric, or intensive care.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Concept Summary

9.1 The Arrhenius Theory

Learning Objective: Can you write reaction equations that illustrate Arrhenius acid–base behavior?

- Arrhenius acids dissociate in water to provide hydrogen ion (H^+).
- Arrhenius bases dissociate in water to provide hydroxide ions (OH^-).

9.2 The Brønsted Theory

Learning Objective: Can you write reaction equations that illustrate Brønsted acid–base behavior, and identify Brønsted acids and bases from written reaction equations?

- Johannes Bronsted and Thomas Lowry proposed a theory for acids and bases.
- Acids are hydrogen-containing substances capable of donating protons to other substances.
- Bases accept and form covalent bonds with protons.
- When a substance behaves as a Brønsted acid by donating a proton, it becomes a conjugate base.

9.3 Naming Acids

Learning Objective: Can you name common acids?

- There are two ways to name acids.
- Water solutions of binary covalent compounds containing hydrogen and a nonmetal are named following the pattern of hydro(stem)ic, where (stem) is the name of the nonmetal bonded to hydrogen.
- Acids in which hydrogen is bonded to polyatomic ions have names based on the name of the polyatomic ion to which the hydrogen is attached.

9.4 The Self-Ionization of Water

Learning Objective: Can you do calculations using the concept of the self-ionization of water?

- Water can behave both as a Brønsted acid and a Brønsted base.
- In pure water, water molecules will transfer protons from one water molecule (an acid) to another (the base).

9.5 The pH Concept

Learning Objective: Can you do calculations using the pH concept?

- The pH is the negative logarithm of the molar H_3O^+ concentration of a solution.
- Solutions with pH values lower than 7 are acidic.
- Solutions with pH values higher than 7 are basic or alkaline.
- Solutions with a pH value of 7 are neutral.

9.6 Properties of Acids

Learning Objective: Can you write reaction equations that illustrate the characteristic reactions of acids?

- Acids have certain characteristics.
- Acids are sour to the taste.
- They react with water to produce H_3O^+.
- They react with solid metallic oxides, hydroxides, carbonates, and bicarbonates.
- They react with certain metals to give hydrogen gas.

9.7 Properties of Bases

Learning Objective: Can you write reaction equations that represent neutralization reactions between acids and bases?

- Basic solutions feel soapy.
- They change color of litmus from red to blue.
- Their most characteristic chemical property is a neutralization reaction with acids to produce water and salt.

9.8 Salts

Learning Objective: Can you write reaction equations that illustrate various ways to prepare salts, and do calculations using the concept of an equivalent of salt?

- Salts are solid crystalline substances at room temperature.
- They contain the cation of a base and the anion of an acid.
- Hydrated salts contain specific numbers of water molecules as a part of their crystalline structures.
- Salts can be prepared by reacting an acid with one of a number of other materials.

9.9 The Strengths of Acids and Bases

Learning Objective: Can you demonstrate an understanding of the words *weak* and *strong* as applied to acids and bases?

- Acids and bases that dissociate completely when dissolved in solution are called strong.
- Those that do not dissociate completely are called weak or moderately weak, depending on the degree of dissociation they undergo.
- Acid strength is indicated by the value of K_a.
- In general, polyprotic acids become weaker acids during each successive dissociation reaction.
- The Brønsted base produced by the dissociation of an acid has a strength opposite that of the acid.
- The acid strengths of cations produced by the dissociation of bases follow a similar pattern.

9.10 Analyzing Acids and Bases

Learning Objective: Can you demonstrate an understanding of the titration technique used to analyze acids and bases?

- The neutralization reaction of acids and bases is used in a process called titration.
- This is how one analyzes acids and bases.
- During a typical titration, a base solution of known concentration is added slowly to an acid solution of unknown concentration.
- The titration is stopped at the endpoint when a color change occurs in an indicator.
- The volumes of acid and base required are used to calculate the acid concentration.

9.11 Titration Calculations

Learning Objective: Can you do calculations related to the analysis of acids and bases by titration?

- Titrations are used to determine the total amount of acid or base in solutions.
- Data collected from titrations are treated like other stoichiometric data in calculations.

9.12 Hydrolysis Reactions of Salts

Learning Objective: Can you explain the concept of salt hydrolysis, and write equations to illustrate the concept?

- The cation and anion of a salt may have the same or different Brønsted acid and base strengths.
- When they are the same, solutions of the salt have a pH of 7.
- When they are different, salt solutions have H_3O^+ and OH^- concentrations that are unequal and pH values different than 7.
- The reactions of salt ions with water that cause these results are called hydrolysis reactions.

9.13 Buffers

Learning Objective: Can you explain how buffers work, and write equations to illustrate their action?

- Solutions that essentially maintain constant pH values when acid (H_3O^+) or base (OH^-) are added are called buffers.
- All buffers have a limit to the amount of acid or base they can absorb without changing pH.
- This limit is called buffer capacity.

Key Terms and Concepts

Acid dissociation constant (9.9)
Acidic solution (9.4)
Activity series (9.6)
Anion (9.8)
Arrhenius acid (9.1)
Arrhenius base (9.1)
Basic or alkaline solution (9.4)
Brønsted acid (9.2)
Brønsted base (9.2)
Buffer (9.13)
Buffer capacity (9.13)
Cation (9.8)
Conjugate acid–base pair (9.2)
Conjugate base (9.2)
Diprotic acid (9.9)
Endpoint of a titration (9.10)
Equivalence point of a titration (9.10)
Equivalent of salt (9.8)
Henderson–Hasselbalch equation (9.13)
Hydrate (9.8)
Hydrolysis reaction (9.12)
Ion product of water (9.4)
Monoprotic acid (9.9)
Neutral (9.4)
Neutralization reaction (9.7)
pH (9.5)
pK_a (9.13)
Salt (9.8)
Strong acids and strong bases (9.9)
Titration (9.10)
Triprotic acid (9.9)
Water of hydration (9.8)
Weak (or moderately weak) acids and bases (9.9)

Key Equations

1. Relationship between $[H_3O^+]$ and $[OH^-]$ in water solutions (**Section 9.4**):	$K_w = [H_3O^+][OH^-] = 1.0 \times 10^{-14}\ (\text{mol/L})^2$	Equation 9.10
2. Relationships between pH and $[H_3O^+]$ (**Section 9.5**):	$\text{pH} = -\log[H_3O^+]$ $[H_3O^+] = 1 \times 10^{-\text{pH}}$	Equation 9.11 Equation 9.12
3. General reactions of acids (**Section 9.8**):	acid + metal → salt + H_2 acid + metal oxide → salt + H_2O acid + metal hydroxide → salt + H_2O acid + metal carbonate → salt + H_2O + CO_2 acid + metal bicarbonate → salt + H_2O + CO_2	Equation 9.26 Equation 9.27 Equation 9.28 Equation 9.29 Equation 9.30
4. Dissociation constant for acids (**Section 9.9**):	$K_a = \frac{[H^+][B^-]}{[HB]}$	Equation 9.34
5. Calculation of buffer pH, Henderson–Hasselbalch equation (**Section 9.13**):	$\text{pH} = \text{p}K_a + \log\frac{[B^-]}{[HB]}$	Equation 9.54

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

The Arrhenius Theory (Section 9.1)

9.1 Write the dissociation equations for the following that emphasize their behavior as Arrhenius acids:

- **a.** HI
- **b.** HBrO
- **c.** HCN
- **d.** $HClO_2$

9.2 Write the dissociation equations for the following that emphasize their behavior as Arrhenius acids:

- **a.** $HBrO_2$
- **b.** HS^-
- **c.** HBr
- **d.** $HC_2H_3O_2$ (only the 1st listed H dissociates)

9.3 Each of the following produces a basic solution when dissolved in water. Identify those that behave as Arrhenius bases and write dissociation equations to illustrate that behavior.

- **a.** CsOH
- **b.** CH_3NH_2
- **c.** NH_3
- **d.** $Ca(OH)_2$

9.4 Each of the following produces a basic solution when dissolved in water. Identify those that behave as Arrhenius bases and write dissociation equations to illustrate that behavior.

- **a.** $NaNH_2$
- **b.** RbOH
- **c.** $C_3H_7NH_2$
- **d.** $Ba(OH)_2$

The Brønsted Theory (Section 9.2)

9.5 Identify each Brønsted acid and base in the following equations. Note that the reactions are assumed to be reversible.

- **a.** $HBr(aq) + H_2O(\ell) \rightleftarrows H_3O^+(aq) + Br^-(aq)$
- **b.** $H_2O(\ell) + N_3^-(aq) \rightleftarrows HN_3(aq) + OH^-(aq)$
- **c.** $H_2S(aq) + H_2O(\ell) \rightleftarrows H_3O^+(aq) + HS^-(aq)$
- **d.** $SO_3^{2-}(aq) + H_2O(\ell) \rightleftarrows HSO_3^-(aq) + OH^-(aq)$
- **e.** $HCN(aq) + H_2O(\ell) \rightleftarrows H_3O^+(aq) + CN^-(aq)$

9.6 Identify each Brønsted acid and base in the following equations. Note that the reactions are assumed to be reversible.

- **a.** $HC_2O_4^-(aq) + H_2O(\ell) \rightleftarrows H_3O^+(aq) + C_2O_4^{2-}(aq)$
- **b.** $HNO_2(aq) + H_2O(\ell) \rightleftarrows H_3O^+(aq) + NO_2^-(aq)$
- **c.** $PO_4^{3-}(aq) + H_2O(\ell) \rightleftarrows HPO_4^{2-}(aq) + OH^-(aq)$
- **d.** $H_2SO_3(aq) + H_2O(\ell) \rightleftarrows HSO_3^-(aq) + H_3O^+(\ell)$
- **e.** $F^-(aq) + H_2O(\ell) \rightleftarrows HF(aq) + OH^-(aq)$

9.7 Identify each conjugate acid–base pair in the equations of Exercise 9.5.

9.8 Identify each conjugate acid–base pair in the equations of Exercise 9.6.

9.9 Write equations to represent the Brønsted acid behavior for each of the following acids in water solution. Remember to represent the reactions as being reversible.

- **a.** HI
- **b.** HBrO
- **c.** HCN
- **d.** HSe^-

9.10 Write equations to represent the Brønsted acid behavior for each of the following acids in water solution. Remember to represent the reactions as being reversible.

- **a.** HF
- **b.** $HClO_3$
- **c.** HClO
- **d.** HS^-

9.11 Write a formula for the conjugate base formed when each of the following behaves as a Brønsted acid:

- **a.** HSO_3^-
- **b.** HPO_4^{2-}
- **c.** $HClO_3$
- **d.** $CH_3NH_3^+$
- **e.** $H_2C_2O_4$

9.12 Write a formula for the conjugate base formed when each of the following behaves as a Brønsted acid:

- **a.** HSO_4^-
- **b.** $CH_3NH_3^+$
- **c.** $HClO_4$
- **d.** NH_4^+
- **e.** HCl

9.13 Write a formula for the conjugate acid formed when each of the following behaves as a Brønsted base:

- **a.** NH_2^-
- **b.** CO_3^{2-}
- **c.** OH^-
- **d.** $(CH_3)_2NH$
- **e.** NO_2^-

9.14 Write a formula for the conjugate acid formed when each of the following behaves as a Brønsted base:

- **a.** HCO_3^-
- **b.** S^{2-}
- **c.** HS^-
- **d.** $HC_2O_4^-$
- **e.** $HN_2O_2^-$

9.15 The following reactions illustrate Brønsted acid–base behavior. Complete each equation.

- **a.** $HI(aq) + ? \rightarrow H_3O^+(aq) + I^-(aq)$
- **b.** $NH_3(\ell) + ? \rightarrow NH_4^+ + NH_2^-$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

c. $H_2C_2O_4(aq) + H_2O(\ell) \rightarrow ? + HC_2O_4^-(aq)$

d. $H_2N_2O_2(aq) + H_2O(\ell) \rightarrow H_3O^+(aq) + ?$

e. $? + H_2O(\ell) \rightarrow H_3O^+(aq) + CO_3^{2-}(aq)$

9.16 The following reactions illustrate Brønsted acid–base behavior. Complete each equation.

a. $H_2AsO_4^-(aq) + NH_3(aq) \rightarrow NH_4^+(aq) + ?$

b. $? + H_2O(\ell) \rightarrow C_6H_5NH_3^+(aq) + OH^-(aq)$

c. $S^{2-}(aq) + ? \rightarrow HS^-(aq) + OH^-(aq)$

d. $? + HBr(aq) \rightarrow (CH_3)_2NH_2^+(aq) + Br^-(aq)$

e. $CH_3NH_2(aq) + HCl(aq) \rightarrow ? + Cl^-(aq)$

9.17* Write equations to illustrate the acid–base reaction when each of the following pairs of Brønsted acids and bases are combined:

	Acid	*Base*
a.	$HOCl$	H_2O
b.	$HClO_4$	NH_3
c.	H_2O	NH_2^-
d.	H_2O	OCl^-
e.	$HC_2O_4^-$	H_2O

9.18* Write equations to illustrate the acid–base reaction when each of the following pairs of Brønsted acids and bases are combined:

	Acid	*Base*
a.	H_3O^+	NH_2^-
b.	$H_2PO_4^-$	NH_3
c.	$HS_2O_3^-$	OCl^-
d.	H_2O	ClO_4^-
e.	H_2O	NH_3

Naming Acids (Section 9.3)

9.19 A water solution of HF gas is used to etch glass. Name the water solution as an acid.

9.20 Hydrogen cyanide, HCN, behaves in a water solution very much like the binary covalent compounds of hydrogen, but it liberates the cyanide ion, CN^-, a deadly poison, which can disrupt the body's ability to utilize oxygen. Name the acidic water solution by following the rules for binary covalent compounds of hydrogen.

9.21 Name the following acids. Refer to **Table 4.7** as needed.

a. $H_2Se(aq)$

b. $HClO_3$

c. H_2SO_4

d. HNO_3

9.22 Name the following acids. Refer to **Table 4.7** as needed.

a. $H_2Te(aq)$

b. $HClO$

c. H_2SO_3

d. HNO_2

9.23 The acid $H_3C_6H_5O_7$ forms the citrate ion, $C_6H_5O_7^{3-}$, when all three hydrogens are removed. Citrate salts belong to a class of drugs known as urinary alkalinizers, used to make urine less acidic. Name the acid.

9.24 The acid $H_2C_4H_4O_4$ forms the succinate ion, $C_4H_4O_4^{2-}$, when both hydrogens are removed. Succinate is used in treating symptoms of menopause and as a topical aid for joint pain. Name $H_2C_4H_4O_4$ as an acid.

9.25 Refer to **Table 4.7**, and write the formula for chromic acid.

9.26 Refer to **Table 4.7**, and write the formula for permanganic acid.

The Self-Ionization of Water (Section 9.4)

9.27 Below are the H_3O^+ concentrations of common foods. Calculate the OH^- concentrations of these items

a. Artichokes, 1.0×10^{-6}

b. Jonathan apples, 4.8×10^{-4}

c. Frozen strawberries, 0.0051

d. Fresh beef, 1.0×10^{-7}

e. Crackers, 6.3×10^{-9}

9.28 Below are the H_3O^+ concentrations of common foods. Calculate the OH^- concentrations of these items.

a. Crab, 1.0×10^{-7}

b. Fruit cocktail, 1.3×10^{-4}

c. Fresh lemon juice, 0.0063

d. Cottage cheese, 1.0×10^{-5}

e. Egg whites, 5.0×10^{-9}

9.29 Below are the OH^- concentrations of common foods. Calculate the H_3O^+ concentrations of these items.

a. Frozen whole eggs, 1.0×10^{-6}

b. Devil's food cake, 5.0×10^{-7}

c. Angel's food cake, 2.6×10^{-9}

d. Fresh grapefruit, 1.3×10^{-11}

e. Egg white solids, 1.0×10^{-7}

9.30 Below are the OH^- concentrations of common foods. Calculate the H_3O^+ concentrations of these items.

a. Pomegranates, 1×10^{-11}

b. Mangos, 1.3×10^{-10}

c. Most freshwater fish, 1.0×10^{-7}

d. Sponge cake, 3.2×10^{-7}

e. Canned tomatoes, 5.0×10^{-11}

9.31 Classify the foods represented in Exercises 9.27 and 9.29 as acidic, basic, or neutral.

9.32 Classify the foods represented in Exercises 9.28 and 9.30 as acidic, basic, or neutral.

The pH Concept (Section 9.5)

9.33 Classify solutions with the following characteristics as acidic, basic, or neutral:

a. Phosphate-free detergent, pH = 10.0

b. Tomato juice, pH = 4.0

c. Saliva, pH = 6.8

d. Household ammonia, pH = 11.6

9.34 Classify solutions with the following characteristics as acidic, basic, or neutral:

a. Vinegar, pH = 2.8

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

b. Bile, pH = 8

c. Black coffee, pH = 5

d. Household bleach, pH = 11

9.35 Determine the pH of water solutions with the following characteristics. Classify each solution as acidic, basic, or neutral.

a. $[H_3O^+] = 1.0 \times 10^{-4}$

b. $[OH^-] = 5.0 \times 10^{-2}$

c. $[H_3O^+] = [OH^-]$

d. $[H_3O^+] = 8.0 \times 10^{-9}$

e. $[OH^-] = 4.0 \times 10^{-10}$

9.36 Determine the pH of water solutions with the following characteristics. Classify each solution as acidic, basic, or neutral.

a. $[H_3O^+] = 4.1 \times 10^{-9}$

b. $[OH^-] = 9.4 \times 10^{-4}$

c. $[OH^-] = 10.[H^+]$

d. $[H_3O^+] = 2.3 \times 10^{-2}$

e. $[OH^-] = 5.1 \times 10^{-10}$

9.37 Determine the pH of water solutions with the following characteristics. Classify each solution as acidic, basic, or neutral.

a. $[H_3O^+] = 6.2 \times 10^{-5}$

b. $[H_3O^+] = 8.4 \times 10^{-8}$

c. $[H_3O^+] = 2.2 \times 10^{-10}$

d. $[OH^-] = 4.9 \times 10^{-2}$

e. $[OH^-] = 6.2 \times 10^{-7}$

9.38 Determine the pH of water solutions with the following characteristics. Classify each solution as acidic, basic, or neutral.

a. $[H_3O^+] = 2.2 \times 10^{-3}$

b. $[H_3O^+] = 3.9 \times 10^{-12}$

c. $[H_3O^+] = 7.5 \times 10^{-6}$

d. $[OH^-] = 2.5 \times 10^{-4}$

e. $[OH^-] = 8.6 \times 10^{-10}$

9.39 The ideal pH for a public swimming pool is considered by many to be pH 7.5. Outside the range of pH 7.2–7.8, exposed eyes will become bloodshot and other adverse effects may be evident. Calculate the following

a. The $[H_3O^+]$ value of pH 7.5

b. The $[H_3O^+]$ value of pH 8.5

c. The multiple difference there is in $[H_3O^+]$ between pH 7.5 and pH 8.5

$$\frac{[H_3O^+]\text{ pH 7.5}}{[H_3O^+]\text{ pH 8.5}}$$

9.40 The pH for a public swimming pool is usually pH 7.2–7.8. Outside that range, exposed eyes will become bloodshot and other adverse effects may be evident. Calculate the following

a. The $[H_3O^+]$ value of pH 7.2

b. The $[H_3O^+]$ value of pH 7.8

c. The multiple difference there is in $[H_3O^+]$ between pH 7.2 and pH = 7.8

$$\frac{[H_3O^+]\text{ pH 7.2}}{[H_3O^+]\text{ pH 7.8}}$$

9.41 Convert the following pH values into both $[H_3O^+]$ and $[OH^-]$ values:

a. pH = 9.00

b. pH = 6.27

c. pH = 3.10

9.42 Convert the following pH values into both $[H_3O^+]$ and $[OH^-]$ values:

a. pH = 3.95

b. pH = 4.00

c. pH = 11.86

9.43 The pH values listed in **Table 9.1** are generally the average values for the listed materials. Most natural materials, such as body fluids and fruit juices, have pH values that cover a range for different samples. Some measured pH values for specific body fluid samples are given below. Convert each one to $[H_3O^+]$, and classify the fluid as acidic, basic, or neutral.

a. Blood, pH = 7.41

b. Gastric juice, pH = 1.60

c. Urine, pH = 5.93

d. Saliva, pH = 6.85

e. Pancreatic juice, pH = 7.85

9.44 The pH values listed in **Table 9.1** are generally the average values for the listed materials. Most natural materials, such as body fluids and fruit juices, have pH values that cover a range for different samples. Some measured pH values for specific body fluid samples are given below. Convert each one to $[H_3O^+]$, and classify the fluid as acidic, basic, or neutral.

a. Bile, pH = 8.05

b. Vaginal fluid, pH = 3.93

c. Semen, pH = 7.38

d. Cerebrospinal fluid, pH = 7.40

e. Perspiration, pH = 6.23

9.45 The pH values of specific samples of food items are listed below. Convert each value to $[H_3O^+]$, and classify the sample as acidic, basic, or neutral.

a. Milk, pH = 6.39

b. Coffee, pH = 5.10

c. Orange juice, pH = 4.07

d. Vinegar, pH = 2.65

9.46 The pH values of specific samples of food items are listed below. Convert each value to $[H_3O^+]$, and classify the sample as acidic, basic, or neutral.

a. Soft drink, pH = 2.91

b. Tomato juice, pH = 4.11

c. Lemon juice, pH = 2.32

d. Grapefruit juice, pH = 3.07

Properties of Acids (Section 9.6)

9.47* Using the information in **Table 9.4**, describe how you would prepare each of the following solutions.

a. About 750 mL of 0.5 M H_2SO_4 from dilute sulfuric acid

b. About 200 mL of 0.1 M NaOH from stock sodium hydroxide solution

c. About 1.0 L of 1 M acetic acid from glacial acetic acid

9.48* Using the information in **Table 9.4**, describe how you would prepare each of the following solutions.

a. About 2 L of 3.0 M HNO_3 from dilute nitric acid solution

b. About 500 mL of 1.5 M aqueous ammonia from concentrated aqueous ammonia solution

c. About 5 L of 0.2 M HCl from concentrated hydrochloric acid solution

9.49 Write balanced molecular equations to illustrate the following characteristic reactions of acids, using nitric acid (HNO_3).

a. Reaction with water to form hydronium ions

b. Reaction with the solid oxide CaO

c. Reaction with the solid hydroxide $Mg(OH)_2$

d. Reaction with the solid carbonate $CuCO_3$

e. Reaction with the solid bicarbonate $KHCO_3$

f. Reaction with Mg metal

9.50 The stomach contains hydrochloric acid (HCl). Write balanced molecular equations to illustrate the following characteristic reactions of acids, in this case HCl, with things you might eat in a daily mineral tablet:

a. Reaction with water to form hydronium ions

b. Reaction with the solid oxide CaO

c. Reaction with the solid hydroxide $Mg(OH)_2$

d. Reaction with the solid carbonate $CuCO_3$

e. Reaction with the solid bicarbonate $KHCO_3$

f. Reaction with Mg metal

9.51* Write each molecular equation of Exercise 9.49 in total ionic and net ionic form. Use **Table 7.4** to decide which products will be soluble.

9.52* Write each molecular equation of Exercise 9.50 in total ionic and net ionic form. Use **Table 7.4** to decide which products will be soluble. Only soluble products can pass through the small intestine's walls into the bloodstream.

9.53 In one of the mechanisms for protection of the stomach, the cells lining the stomach release HCO_3^-, bicarbonate ions, to react with stomach acid, HCl. Write a reaction for $NaHCO_3$ and HCl.

9.54 Aluminum hydroxide, $Al(OH)_3$, is an ingredient in some antacids. Write a reaction for the neutralization of stomach acid, HCl, with $Al(OH)_3$.

9.55* Write balanced molecular, total ionic, and net ionic equations to illustrate each of the following reactions. All the metals form 2+ ions.

a. Zinc with H_2SO_4

b. Magnesium with HCl

c. Calcium with $HC_2H_3O_2$

9.56* Write balanced molecular, total ionic, and net ionic equations to illustrate each of the following reactions. All the metals form 2+ ions.

a. Tin with H_2SO_3

b. Magnesium with H_3PO_4

c. Calcium with HBr

Properties of Bases (Section 9.7)

9.57* Write balanced molecular, total ionic, and net ionic equations to represent neutralization reactions between RbOH and the following acids. Use all H's possible for each acid.

a. HCl

b. HNO_3

c. H_2SO_4

9.58* Write balanced molecular, total ionic, and net ionic equations to represent neutralization reactions between RbOH and the following acids. Use all H's possible for each acid.

a. H_3PO_4

b. $H_2C_2O_4$ (oxalic acid)

c. $HC_2H_3O_2$

9.59 Carbonic acid (H_2CO_3) and phosphoric acid (H_3PO_4) are polyprotic acids that can form more than one salt, depending on the number of H's that react with base. In the body, carbonic acid plays an important role in maintaining acid–base homeostasis via the bicarbonate-buffer system. Phosphoric acid is added to foods and some cola beverages to provide a tangy, sour taste. Write balanced molecular, total ionic, and net ionic equations to represent the following neutralization reactions between KOH and

a. H_2CO_3 (react only one H)

b. H_2CO_3 (react both H's)

c. H_3PO_4 (react only one H)

9.60 Oxalic acid ($H_2C_2O_4$) and phosphoric acid (H_3PO_4) are polyprotic acids that can form more than one salt, depending on the number of H's that react with base. Oxalic acid is found in plants such as spinach, cabbage, broccoli, and brussel sprouts. Phosphoric acid is added to foods and some cola beverages to provide a tangy, sour taste. Write balanced molecular, total ionic, and net ionic equations to represent the following neutralization reactions between KOH and

a. H_3PO_4 (react two H's)

b. H_3PO_4 (react three H's)

c. $H_2C_2O_4$ (react one H)

Salts (Section 9.8)

9.61 Identify with ionic formulas the cations and anions of the following salts:

a. LiCl

b. $Cu(NO_3)_2$

c. $SrSO_4$

d. K_3PO_4

e. K_2HPO_4

f. $CaCO_3$

9.62 Identify with ionic formulas the cations and anions of the following salts:

a. NH_4NO_3

b. $CaCl_2$

c. $Mg(HCO_3)_2$

d. $KC_2H_3O_2$

e. $LiHSO_3$

9.63 Identify with formulas the acid and base from which the anion and cation of each salt in Exercise 9.61 was derived. Pay special attention to salts derived from polyprotic acids and be sure to list the acid formula with all H's.

9.64 Identify with formulas the acid and base from which the anion and cation of each salt in Exercise 9.62 was derived. Pay special attention to salts derived from polyprotic acids and be sure to list the acid formula with all H's.

9.65 Calculate the mass of water that would be released if the water of hydration were completely driven off 1.0 mol of (a) plaster of Paris and (b) gypsum (see **Table 9.6**). How would the products of these reactions compare?

9.66 Calculate the mass of water that would be released if the water of hydration were completely driven off 1.0 mol of (a) Epsom salts and (b) borax (see **Table 9.6**). How would the products of these reactions compare?

9.67 Write formulas for the acid and indicated solid that could be used to prepare each of the following salts:

a. $CuCl_2$ (solid is an oxide)

b. $MgSO_4$ (solid is a carbonate)

c. LiBr (solid is a hydroxide)

9.68 Write formulas for the acid and indicated solid that could be used to prepare each of the following salts:

a. KNO_3 (solid is a bicarbonate)

b. $ZnCl_2$ (solid is a metal)

c. LiBr (solid is an oxide)

9.69 Write balanced molecular equations to illustrate each salt preparation described in Exercise 9.67.

9.70 Write balanced molecular equations to illustrate each salt preparation described in Exercise 9.68.

9.71 Determine the number of moles of each of the following salts that would equal 1 eq of salt:

a. KNO_3

b. Li_2CO_3

c. $SrCl_2$

9.72 Determine the number of moles of each of the following salts that would equal 1 eq of salt:

a. $MgCO_3$

b. $Zn(HCO_3)_2$

c. $FeCl_3$

9.73 Blood plasma levels of electrolytes are often reported in milliequivalents (meq) or in millimoles (mmol). Given below are the results of a blood test. Convert these results from meq to mmol.

a. Magnesium (Mg^{2+}), 3 meq/L

b. Bicarbonate (HCO_3^-), 27 meq/L

c. Chloride (Cl^-), 103 meq/L

9.74 Blood plasma levels of electrolytes are often reported in milliequivalents (meq) or in millimoles (mmol). Below are given the results of a blood test. Convert these results from meq to mmol.

a. Sodium (Na^+) 142 meq/L

b. Phosphate (PO_4^{3-}) 2 meq/L

c. Sulfate (SO_4^{2-}) 1 meq/L

9.75 Determine the number of equivalents and milliequivalents in 5.00 g of each of the following salts. Include any waters of hydration given in the salt formula when you calculate salt formula weights.

a. NaCl

b. $NaNO_3$

c. Na_3PO_4

d. $MgSO_4 \cdot 7H_2O$

9.76 Determine the number of equivalents and milliequivalents in 5.00 g of each of the following salts. Include any waters of hydration given in the salt formula when you calculate salt formula weights.

a. $Na_2CO_3 \cdot 10H_2O$

b. $CuSO_4 \cdot 5H_2O$

c. Li_2CO_3

d. NaH_2PO_4

9.77* A sample of intracellular fluid contains 45.1 meq/L of Mg^{2+} ion. Assume the Mg^{2+} comes from dissolved $MgCl_2$, and calculate the number of moles and number of grams of $MgCl_2$ that would be found in 250. mL of the intracellular fluid.

9.78* A sample of intracellular fluid contains 133 meq/L of K^+ ion. Assume the K^+ comes from dissolved K_2SO_4, and calculate the number of moles and number of grams of K_2SO_4 that would be found in 150. mL of the intracellular fluid.

The Strengths of Acids and Bases (Section 9.9)

9.79 Illustrate the difference between weak, moderately weak, and strong acids by writing dissociation reactions for the hypothetical acid HB, using arrows of various lengths.

9.80 The K_a values have been determined for four acids and are listed below. Arrange the acids in order of increasing acid strength (weakest first, strongest last).

acid A ($K_a = 5.6 \times 10^{-5}$)

acid B ($K_a = 1.8 \times 10^{-5}$)

acid C ($K_a = 1.3 \times 10^{-4}$)

acid D ($K_a = 1.1 \times 10^{-3}$)

9.81 Arrange the four acids classified as weak in **Table 9.7** in order of increasing strength (weakest first, strongest last).

9.82 K_a values for four weak acids are given below:

acid A ($K_a = 2.6 \times 10^{-4}$)

acid B ($K_a = 3.7 \times 10^{-5}$)

acid C ($K_a = 5.8 \times 10^{-4}$)

acid D ($K_a = 1.5 \times 10^{-3}$)

a. Arrange the four acids in order of increasing acid strength (weakest first, strongest last).

b. Arrange the conjugate bases of the acids (identify as base A, etc.) in order of increasing base strength (weakest base first, strongest last).

9.83 Write dissociation reactions and K_a expressions for the following weak acids:

a. Hypobromous acid, HBrO

b. Sulfurous acid, H_2SO_3 (1st H only)

c. Hydrogen sulfite ion, HSO_3^-

d. Hydroselenic acid, H_2Se (1st H only)

e. Arsenic acid, H_3AsO_4 (1st H only)

9.84 Write dissociation reactions and K_a expressions for the following weak acids:

a. Hydrogen selenide ion, HSe^-

b. Dihydrogen borate ion, $H_2BO_3^-$ (1st H only)

c. Hydrogen borate ion, HBO_3^{2-}

d. Hydrogen arsenate ion, $HAsO_4^{2-}$

e. Hypochlorous acid, HClO

9.85 Equal molar solutions are made of three monoprotic acids, HA, HB, and HC. The pHs of the solutions are, respectively, 4.82, 3.16, and 5.47. Rank the acids in the order of increasing acid strength and explain your reasoning.

9.86 If someone asked you for a weak acid solution, which of the following would you provide according to definitions in this chapter?

a. 0.05 M HCl

b. 20% acetic acid

If the individual really wanted the other solution, what term should have been used instead of *weak*?

9.87 Arsenic acid (H_3AsO_4) is a moderately weak triprotic acid. Write equations showing its stepwise dissociation. Which of the three anions formed in these reactions will be the strongest Brønsted base? Which will be the weakest Brønsted base? Explain your answers.

Analyzing Acids and Bases (Section 9.10)

9.88 Explain the purpose of doing a titration.

9.89 Describe the difference between the information obtained by measuring the pH of an acid solution and by titrating the solution with base.

9.90 Suppose a student is going to titrate an acidic solution with a base and just picks an indicator at random. Under what circumstances will (a) the endpoint and equivalence point be the same? (b) The endpoint and equivalence point be different?

9.91 Determine the number of moles of NaOH that could be neutralized by each of the following:

a. 1.00 L of 0.250 M HCl

b. 500. mL of 0.300 M HNO_3

9.92 Determine the number of moles of NaOH that could be neutralized by each of the following:

a. 250.0 mL of 0.400 M HBr

b. 750.0 mL of 0.300 M $HClO_4$

Titration Calculations (Section 9.11)

9.93 Write a balanced molecular equation to represent the neutralization reaction between NaOH and each of the following acids. React all of the acid H's.

a. Molybdic acid, H_2MoO_4

b. Permanganic acid, $HMnO_4$

c. Phosphoric acid, H_3PO_4

9.94 Write a balanced molecular equation to represent the neutralization reaction between NaOH and each of the following acids. React all of the acid H's.

a. Trichloroacetic acid, $HC_2O_2Cl_3$

b. Dithionic acid, $H_2S_2O_6$

c. Hypophosphorous acid, $H_4P_2O_6$

9.95 Write a balanced molecular equation to represent the neutralization reaction between HCl and each of the following bases:

a. $Cd(OH)_2$

b. $Cr(OH)_3$

c. $Fe(OH)_2$

9.96 Write a balanced molecular equation to represent the neutralization reaction between HCl and each of the following bases:

a. $Zn(OH)_2$

b. $Tl(OH)_3$

c. CsOH

9.97* A 25.00 mL sample of gastric juice is titrated with a 0.0210 M NaOH solution. The titration to the equivalence point requires 26.4 mL of NaOH solution. If the equation for the reaction is

$$HCl(aq) + NaOH(aq) \rightarrow NaCl(aq) + H_2O(\ell)$$

what is the molarity of HCl in the gastric juice?

9.98 Oxalic acid, $H_2C_2O_4$, is present in a number of foodstuffs but can be toxic if ingested in larger amounts. For this reason, rhubarb leaves are not consumed. A 25.00 mL sample of $H_2C_2O_4$ solution required 43.88 mL of 0.1891 M NaOH solution to titrate it to the equivalence point. Calculate the molarity of the $H_2C_2O_4$ solution.

9.99* A 20.00 mL sample of each of the following acid solutions is to be titrated to the equivalence point using a 0.120 M NaOH solution. Determine the number of milliliters of NaOH solution that will be needed for each acid sample.

a. 0.200 M HCl

b. 0.200 M H_2SO_4

c. 0.250 M HCl

d. 10.00 g of H_3PO_4 in 150.0 mL of solution

e. 0.150 mol H_2MoO_4 in 400.0 mL of solution

f. 0.215 mol H_2MoO_4 in 600.0 mL of solution

9.100* A 20.00 mL sample of each of the following acid solutions is to be titrated to the equivalence point using a 0.120 M NaOH solution. Determine the number of milliliters of NaOH solution that will be needed for each acid sample.

a. 0.200 M $HClO_4$

b. 0.125 M H_2SO_4

c. 0.150 M $H_4P_2O_6$

d. 0.120 mol H_3PO_4 in 500.0 mL of solution

e. 6.25 g of H_2SO_4 in 250.0 mL of solution

f. 0.500 mol $HClO_3$ in 1.00 L of solution

9.101* The following acid solutions were titrated to the equivalence point with the base listed. Use the titration data to calculate the molarity of each acid solution.

- **a.** 25.00 mL of HI solution required 27.15 mL of a 0.250 M NaOH solution.
- **b.** 20.00 mL of H_2SO_4 solution required 11.12 mL of a 0.109 M KOH solution.
- **c.** 25.00 mL of gastric juice (HCl) required 18.40 mL of a 0.0250 M NaOH solution.

9.102* The following acid solutions were titrated to the equivalence point with the base listed. Use the titration data to calculate the molarity of each acid solution.

- **a.** 5.00 mL of dilute H_2SO_4 required 29.88 mL of a 1.17 M NaOH solution.
- **b.** 10.00 mL of vinegar (acetic acid) required 35.62 mL of a 0.250 M KOH solution.
- **c.** 10.00 mL of muriatic acid (HCl) used to clean brick and cement required 20.63 mL of a 6.00 M NaOH solution.

9.103* A 20.00-mL sample of diprotic oxalic acid ($H_2C_2O_4$) solution is titrated with a 0.250 M NaOH solution. A total of 26.54 mL of NaOH is required. Calculate:

- **a.** The number of moles of oxalic acid in the 20.00-mL sample.
- **b.** The molarity of the oxalic acid solution.
- **c.** The number of grams of oxalic acid in the 20.00-mL sample.

9.104* A sample of monoprotic benzoic acid weighing 0.5823 g is dissolved in about 25 mL of water. The solution is titrated to the equivalence point using 0.1021 M NaOH. The volume of base required is 46.75 mL. Calculate the molecular weight of the solid acid.

Hydrolysis Reactions of Salts (Section 9.12)

9.105 A solution of solid NH_4Cl dissolved in pure water is acidic (the pH is less than 7). Explain.

9.106 A solution of solid Na_3PO_4 dissolved in pure water is basic (the pH is greater than 7). Explain.

9.107 Predict the relative pH (greater than 7, less than 7, etc.) for water solutions of the following salts. **Table 9.9** may be useful. For each solution in which the pH is greater or less than 7, explain why and write a net ionic equation to justify your answer.

- **a.** Potassium sulfite, K_2SO_3
- **b.** Lithium nitrite, $LiNO_2$
- **c.** Sodium carbonate, Na_2CO_3
- **d.** Methylammonium chloride, CH_3NH_3Cl (CH_3NH_2 is a weak base)

9.108 Predict the relative pH (greater than 7, less than 7, etc.) for water solutions of the following salts. **Table 9.9** may be useful. For each solution in which the pH is greater or less than 7, explain why and write a net ionic equation to justify your answer.

- **a.** Sodium hypochlorite, NaOCl (HOCl is a weak acid)
- **b.** Sodium formate, $NaCHO_2$
- **c.** Potassium nitrate, KNO_3
- **d.** Sodium phosphate, Na_3PO_4

9.109* A chemist has 20.00 mL samples of 0.100 M acid A and 0.100 M acid B in separate flasks. Both acids are monoprotic. Unfortunately, the flasks were not labeled, so the chemist doesn't know which sample is in which flask. But fortunately, it is known that acid A is strong and acid B is weak. Before thinking about the problem, the chemist adds 20.00 mL of 0.100 M NaOH solution to each flask. Explain how the chemist could use a pH meter (or pH paper) to determine which flask originally contained which acid.

9.110 Explain why the hydrolysis of salts makes it necessary to have available in a laboratory more than one acid–base indicator for use in titrations.

9.111 How would the pH values of equal molar solutions of the following salts compare (highest, lowest, etc.)? NaH_2PO_4, Na_2HPO_4, and Na_3PO_4.

Buffers (Section 9.13)

9.112 Write equations similar to Equations 9.48 and 9.49 of the text to illustrate how a mixture of sodium hydrogen phosphate (Na_2HPO_4) and sodium dihydrogen phosphate (NaH_2PO_4) could function as a buffer when dissolved in water. Remember that phosphoric acid (H_3PO_4) ionizes in three steps.

9.113 Could a mixture of ammonia (NH_3), a weak base, and ammonium chloride (NH_4Cl) behave as a buffer when dissolved in water? Use reaction equations to justify your answer.

9.114 Some illnesses lead to a condition of excess acid (acidosis) in the body fluids. An accepted treatment is to inject solutions containing bicarbonate ions (HCO_3^-) directly into the bloodstream. Write an equation to show how this treatment would help combat the acidosis.

9.115 Calculate the pH of a buffer made by dissolving 1 mol formic acid (HCOOH) and 1 mol sodium formate (HCOONa) in 1 L of solution (see **Table 9.9**).

9.116
- **a.** Calculate the pH of a buffer that is 0.1 M in lactic acid, $C_2H_4(OH)COOH$, and 0.1 M in sodium lactate, $C_2H_4(OH)COONa$.
- **b.** What is the pH of a buffer that is 1 M in lactic acid and 1 M in sodium lactate?
- **c.** What is the difference between the buffers described in parts a and b?

9.117 Which of the following acids and its conjugate base would you use to make a buffer with a pH of 3.00? Explain your reasons: formic acid, lactic acid, nitrous acid.

9.118 Calculate the pH of buffers that contain the acid and conjugate base concentrations listed below.

- **a.** $[CH_3COOH] = 0.40$ M, $[CH_3COO^-] = 0.25$ M
- **b.** $[H_2PO_4^-] = 0.10$ M, $[HPO_4^{2-}] = 0.40$ M
- **c.** $[HSO_3^-] = 1.50$ M, $[SO_3^{2-}] = 0.20$ M

9.119 Calculate the pH of buffers that contain the acid and conjugate base concentrations listed below.

- **a.** $[HPO_4^{2-}] = 0.33$ M, $[PO_4^{3-}] = 0.52$ M
- **b.** $[HNO_2] = 0.029$ M, $[NO_2^-] = 0.065$ M
- **c.** $[HCO_3^-] = 0.50$ M, $[CO_3^{2-}] = 0.15$ M

9.120 What ratio of concentrations of NaH_2PO_4 and Na_2HPO_4 in solution would give a buffer with pH = 7.65?

9.121 A citric acid–citrate buffer has a pH of 3.20. You want to increase the pH to a value of 3.35. Would you add citric acid or sodium citrate to the solution? Explain.

Additional Exercises

9.122 Consider the following reaction equation:

$$Cl^-(aq) + H_3O^+(aq) \rightarrow HCl(aq) + H_2O(\ell)$$

Draw Lewis structures (electron-dot formulas) for all the substances in the reaction equation, identify each reactant as a Brønsted acid or base, and then propose a definition for an acid and a base based on the ability of the substance to accept or donate a pair of electrons to form a covalent bond.

9.123 Consider the following dissociation reaction of a weak acid, HA:

$$HA(aq) + H_2O(\ell) \rightleftarrows H_3O^+(aq) + A^-(aq)$$

It was determined that 2.63% of the acid in a 0.150 M solution of HA in water was dissociated. Calculate the pH of the 0.150 M solution.

9.124 The value of K_w for water varies with temperature. At 25°C, $K_w = 1.0 \times 10^{-14}$. At 50°C, $K_w = 5.5 \times 10^{-14}$. Calculate the pH of water at 50°C.

9.125 When sodium metal, Na, reacts with water, hydrogen gas, H_2, and sodium hydroxide, NaOH, in solution are produced. Write a balanced equation for the reaction, and explain how a basic solution is produced.

Chemistry for Thought

9.126 In an early industrial method, H_2SO_4 was manufactured in lead-lined chambers. Propose an explanation for this.

9.127 A saturated solution of solid $Ca(OH)_2$ in water has a $[OH^-]$ of only 2.50×10^{-2} M, and yet $Ca(OH)_2$ is a strong base. Explain this apparent contradiction.

9.128 Imagine that a solution of weak acid is being titrated with a strong base. Describe the substances present in the solution being titrated when it has been titrated halfway to the equivalence point. How is the pH of this half-titrated solution related to the pK_a for the weak acid?

9.129 Calculate K_a for the following weak acids based on the equilibrium concentrations and pH values given:

a. Benzoic acid, represented by HBz:

$pH = 2.61$, $[Bz^-] = 2.48 \times 10^{-3}$, $[HBz] = 0.0975$

b. Abietic acid, represented by HAb:

$pH = 4.16$, $[Ab^-] = 6.93 \times 10^{-5}$, $[HAb] = 0.200$

c. Cacodylic acid, represented by HCc:

$pH = 3.55$, $[Cc^-] = 0.000284$, $[HCc] = 0.150$

9.130 Bottles of ketchup are routinely left on the counters of cafés, yet the ketchup does not spoil. Why not?

9.131 Lactate ion ($C_3H_5O_3^-$) is a weak base often used in intravenous solutions. Write an equation for the reaction of lactate ion with water.

9.132 Refer to **Figure 9.10** and answer the question. Do you think the results would be the same if sulfuric acid (H_2SO_4) were substituted for the HCl? Explain.

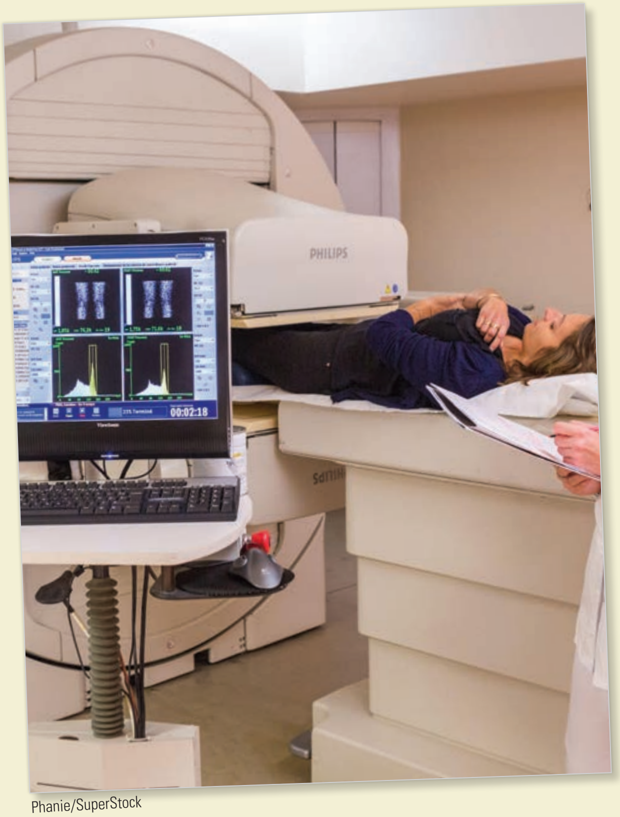
9.133 Refer to **Figure 9.18**. Which of the three indicators would be the best to use to differentiate between the solutions with pH values of 4 and 6?

9.134 Refer to **Figure 9.19** and explain why the pH reading of the meter might not be 7.00 at the equivalence point in a titration. Would the pH at the equivalence point be greater or less than 7 if hydrochloric acid were titrated with aqueous ammonia?

9.135 Refer to **Figure 9.20** and answer the question. List at least two other ions that would behave like the Na^+ ion.

9.136 Refer to **Figure 9.21** and answer the question. What color is the universal indicator in acidic solutions? In basic solutions? Explain how you arrived at your conclusions.

10 Radioactivity and Nuclear Processes


Phanie/SuperStock

Health Career Focus

NUCLEAR MEDICINE TECHNOLOGIST

"It feels a little like a superpower," I explain to the classroom of radiology students. "I put on a protective suit to pick up the radioactive medication; then I connect it to the IV, or in some cases, 'port' and the medicine produces a 'contrast,' allowing the radiologists to see minute details. Without these medications, doctors couldn't make the accurate diagnoses needed for cancer treatment."

"Some of the medications I administer are for diagnosis, and some are for treatment, and most are radioactive. That's why I'm called a 'nuclear medicine' technologist."

Students pay keen attention when I show images of scans comparing normal and diseased patients. I feel proud when scans document improvement over time from treatments I've administered.

"I know my work gives many patients days, or even years, of life they might not otherwise enjoy—that really feels like a super power."

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary.*

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Describe and characterize the common forms of radiation emitted during radioactive decay and other nuclear processes. **(Section 10.1)**
2. Write balanced equations for nuclear reactions. **(Section 10.2)**
3. Solve problems using the half-life concept. **(Section 10.3)**
4. Describe the effects of radiation on health. **(Section 10.4)**
5. Describe and compare the units used to measure quantities of radiation. **(Section 10.5)**
6. Describe, with examples, medical uses of radioisotopes. **(Section 10.6)**
7. Describe, with examples, nonmedical uses of radioisotopes. **(Section 10.7)**
8. Show that you understand the concept of induced nuclear reactions. **(Section 10.8)**
9. Describe the differences between nuclear fission and nuclear fusion reactions. **(Section 10.9)**

IN CHAPTERS 3 AND 4, we learned that the arrangements of electrons around the nuclei of atoms determine the chemical behavior of elements and compounds. We saw that chemical reactions take place between atoms and molecules as electrons rearrange to achieve noble gas configurations for the atoms involved. These noble gas configurations represent a stable arrangement for the electrons. In this chapter, we will see that the achievement of stability is also a driving force that causes certain atomic nuclei to undergo changes that release small subnuclear particles and energy.

10.1 Radioactive Nuclei

Learning Objective 1 Describe and characterize the common forms of radiation emitted during radioactive decay and other nuclear processes.

In 1896 Henri Becquerel, a French physicist, discovered that uranium compounds emitted rays that could expose and fog photographic plates wrapped in lightproof paper. Research conducted since that time has shown that the penetrating rays originate from changes that occur in the nuclei of some atoms. We saw in **Section 2.3** that isotopes of the same element differ only in the number of neutrons present in their nuclei. Thus, each of the three isotopes of hydrogen, represented by the symbols $^{1}_{1}\text{H}$, $^{2}_{1}\text{H}$, and $^{3}_{1}\text{H}$, contains one proton in the nucleus and one electron outside the nucleus. However, besides the one nuclear proton, $^{2}_{1}\text{H}$ and $^{3}_{1}\text{H}$ contain one and two nuclear neutrons, respectively. It has been found that some combinations of neutrons and protons in the nucleus are stable and do not change spontaneously, but some combinations are not stable. It is these unstable nuclei that emit radiation as they become more stable. For example, both $^{1}_{1}\text{H}$ and $^{2}_{1}\text{H}$ are stable, but $^{3}_{1}\text{H}$ emits radiation. Nuclei that emit radiation are said to be **radioactive nuclei**.

radioactive nuclei Nuclei that undergo spontaneous changes and emit energy in the form of radiation.

Henri Becquerel discovered natural radioactivity by chance. Through research, he found that radiation was emitted by any compound of uranium. He further found that the intensity of the radiation was unaffected by factors that normally influence the rates of chemical reactions: the temperature, pressure, and type of uranium compound used.

Later studies by other investigators showed that the radiation emitted by uranium, and by other radioactive elements discovered later, could be separated into three types by an electrical or magnetic field (see **Figure 10.1**). The three types had different electrical charges: One was positive, one was negative, and one carried no charge. The types of radiation were given names that are still used today: alpha rays (positive), beta rays (negative), and gamma rays (uncharged).

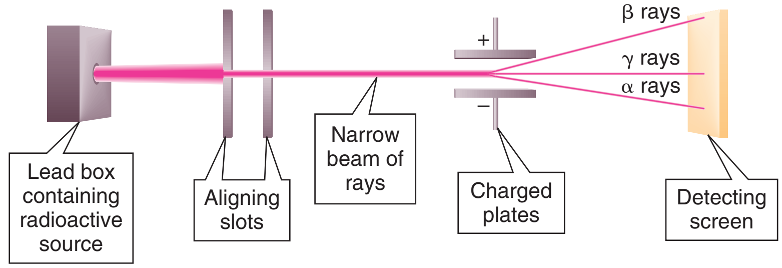


FIGURE 10.1 The three types of emitted radiation.

Today it is known that other types of radiation, such as neutrons and positrons, are also emitted by radioactive nuclei. However, alpha, beta, and gamma are the most common. **Table 10.1** summarizes the characteristics of these forms. In this book, we usually use the symbol given first for each form; the symbols in parentheses are alternatives you might

TABLE 10.1 Characteristics of Nuclear Radiation

Type of Radiation	Symbols	Mass Number	Charge	Composition
Alpha	$^{4}_{2}\alpha$ (α, $^{4}_{2}$He, He^{2+})	4	$+2$	Helium nuclei, 2 protons + 2 neutrons
Beta	$^{0}_{-1}\beta$ (β, β^{-}, $^{0}_{-1}$e, e^{-})	0	-1	Electrons produced in nucleus and ejected
Gamma	γ ($^{0}_{0}\gamma$)	0	0	Electromagnetic radiation
Neutron	$^{1}_{0}$n (n)	1	0	Neutrons
Positron	$^{0}_{1}\beta$ (β^{+}, $^{0}_{1}$e, e^{+})	0	$+1$	Positive electrons

find elsewhere. Except for gamma radiation, which is very high-energy radiation somewhat like X-rays, the radiation emitted by radioactive nuclei consists of streams of particles. The emission of radiation by unstable nuclei is often called **radioactive decay**.

radioactive decay A process in which an unstable nucleus changes energy states and in the process emits radiation.

We note from **Table 10.1** that the particles that make up alpha rays are identical to the nuclei of helium atoms; that is, they are clusters containing two protons and two neutrons. Because they are positively charged, alpha particles are attracted toward the negatively charged plate in **Figure 10.1**. **Alpha particles** move at a speed of nearly one-tenth the speed of light. They are the most massive particles emitted by radioactive materials, and they have the highest charge. Because of their mass and charge, they collide often with molecules of any matter through which they travel. As a result of these collisions, their energy is quickly dissipated, and they do not travel far. They cannot even penetrate through a few sheets of writing paper or the outer cells of the skin. However, exposure to intense alpha radiation can result in severe burns of the skin.

alpha particle The particle that makes up alpha rays. It is identical to the helium nucleus and is composed of two protons and two neutrons.

Beta particles are actually electrons, but they are produced within the nucleus and then emitted. They are not part of the group of electrons moving around the nucleus that is responsible for chemical characteristics of the atoms. Beta particles have a smaller charge than alpha particles and are also 7000 times less massive than alpha particles. They undergo far fewer collisions with molecules of matter through which they pass and therefore are much more penetrating than alpha particles. Because of their negative charge and tiny mass, beta particles are attracted toward the positive plate of **Figure 10.1**, and are deflected more than alpha particles.

beta particle The particle that makes up beta rays. It is identical to an electron but is produced in the nucleus when a neutron is changed into a proton and an electron.

Gamma rays are not streams of particles but rays of electromagnetic radiation similar to X-rays that have higher energies. Like X-rays, gamma radiation is very penetrating and dangerous to living organisms. Adequate shielding from gamma rays is provided only by thick layers of heavy materials like metallic lead or concrete. Because they are not charged, gamma rays are not attracted to either charged plate in **Figure 10.1**.

gamma ray A high-energy ray that is like an X-ray, but with a higher energy.

radioisotope An isotope of an element that emits nuclear radiation.

10.2 Equations for Nuclear Reactions

Learning Objective 2 Write balanced equations for nuclear reactions.

Isotopes of elements that emit nuclear radiation are called **radioisotopes** (see **Figure 10.2**). In nuclear reactions, a specific isotope of an element may behave differently from another isotope of the same element. Thus, all particles involved in nuclear reactions are designated by a symbol, a mass number (the sum of protons and neutrons in the particle), and an atomic number (or charge for electrons or positrons). The symbolism used was introduced in **Section 2.3**. It is $^{A}{}_{Z}X$, where X is the symbol for the particle, A is the mass number, and Z is the atomic number or charge. When X represents the nucleus of an isotope of an element, the chemical symbol for the element is generally used.

SpeedKingz/Shutterstock.com

FIGURE 10.2 The radioisotope americium-241 is present in smoke detectors. Am-241 emits alpha particles, which conduct electricity. The presence of smoke reduces electrical conductivity, sounding the alarm.

Example 10.1 Writing Symbols for Particles

Write appropriate symbols for the following particles using the $^{A}_{Z}X$ symbolism:

a. An iodine-123 nucleus, which is used in the diagnosis of thyroid cancer
b. An alpha particle
c. A deuteron, a particle containing one proton and one neutron

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Solution

a. Iodine-123 is an isotope of iodine, so the symbol X is replaced by I. The mass number is 123 according to the rules learned earlier for designating isotopes, so $A = 123$. The atomic number of iodine obtained from the periodic table is 53, so $Z = 53$, and the symbol is $^{123}_{53}\mathrm{I}$.

b. An alpha particle is represented by the symbol α. Since it contains two protons and two neutrons, $A = 4$ and $Z = 2$. The symbol is $^{4}_{2}\alpha$, as shown in **Table 10.1**.

c. A deuteron is not familiar to you, so we will replace its symbol X with D. It contains one proton and one neutron, so $A = 2$ and $Z = 1$. The symbol is $^{2}_{1}D$. This particle is the nucleus of a deuterium or heavy hydrogen atom and so could also be represented as $^{2}_{1}\mathrm{H}$.

✔ **LEARNING CHECK 10.1** Write appropriate symbols for the following particles using the $^{A}_{Z}X$ symbolism:

a. An iodine-131 nucleus

b. A beta particle

c. A hypothetical particle composed of four protons

d. A hypothetical particle composed of four electrons

A nuclear equation is balanced when the sum of the atomic numbers on the left side equals the sum of the atomic numbers on the right side and the sum of the mass numbers on the left equals the sum of the mass numbers on the right. Thus, we focus on mass numbers and atomic numbers in nuclear reactions. As shown in the following example, a nucleus of an element that undergoes a nuclear reaction by emitting a particle is changed to a nucleus of a different element.

Example 10.2 Equations for Nuclear Reactions

Uranium-238 nuclei undergo radioactive decay by emitting an alpha particle and changing into the nucleus of another element. Write a balanced nuclear equation for the process.

Solution

Because the uranium-238 nucleus gives up an alpha particle, $^{4}_{2}\alpha$, the mass number of the uranium-238 must decrease by 4 and the atomic number must decrease by 2. As a result, the new nucleus, called a **daughter nucleus**, has a mass number of 234 and an atomic number of 90 (remember, the atomic number of uranium can be obtained from a periodic table). The balanced nuclear equation is

daughter nuclei The new nuclei produced when unstable nuclei undergo radioactive decay.

$$^{238}_{92}\mathrm{U} \rightarrow {}^{4}_{2}\alpha + {}^{234}_{90}\mathrm{Th}$$

Note that this equation is balanced because

$$238 = 4 + 234 \qquad \text{and} \qquad 92 = 2 + 90$$

The symbol for the daughter nucleus (thorium) was obtained by locating element number 90 in the periodic table.

Processes such as this where one alpha particle is ejected can be represented by the general equation

$$^{A}_{Z}X \rightarrow {}^{4}_{2}\alpha + {}^{A-4}_{Z-2}Y$$

where Y is the symbol of the daughter nucleus.

✔ **LEARNING CHECK 10.2** Thorium, element number 90, exists in a number of isotopic forms. One form, thorium-234, decays by emitting a beta particle. Write a balanced nuclear equation for the process and write a general equation for decays in which one beta particle is ejected.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

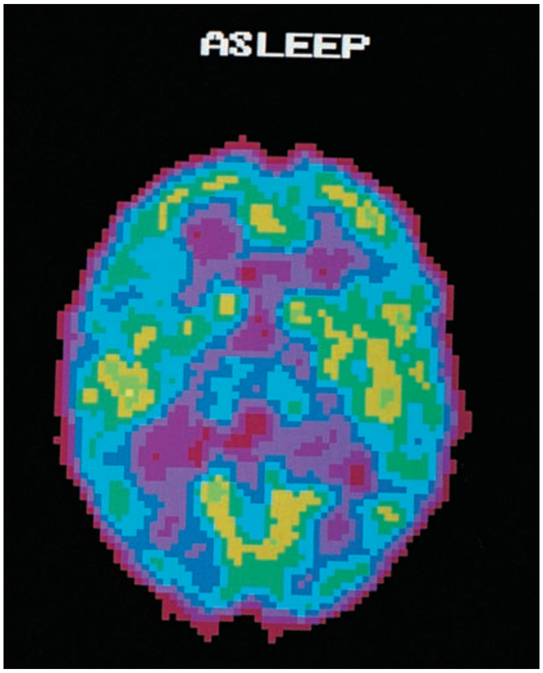
Because gamma rays have no mass or atomic numbers, they do not enter into the balancing process of nuclear reactions. However, they do represent energy and should be included in balanced equations when they are known to be emitted.

As described earlier, beta particles are electrons ejected from the nucleus of a radioactive atom, and yet, we know from our discussions of atomic theory in Chapter 2 that atomic nuclei contain only protons and neutrons. Where then do the beta particles originate? According to a simplified theory of nuclear behavior, a beta particle (or electron) is produced in the nucleus when a neutron changes into a proton. The balanced equation for the nuclear reaction is

$$^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\beta \qquad (10.1)$$

positron A positively charged electron.

Note that the criteria for balance in this equation are satisfied; that is, $1 = 1 + 0$ and $0 = 1 + (-1)$. Thus, a nuclear neutron is converted to a proton during beta emission, and the daughter nucleus has an atomic number higher by 1 than the decaying nucleus. You found this result if you did Learning Check 10.2 correctly. Similar changes in nuclear particles occur during two other types of nuclear reactions. Some nuclei decay by positron emission. A **positron** is a positively charged electron with the ${}^{0}_{1}\beta$ (see **Table 10.1**). When a nucleus emits a positron, a nuclear proton is changed to a neutron. Positron-emitting isotopes are used in diagnostic PET scans of the brain (see **Figure 10.3**).



Hank Morgan/Science Source

FIGURE 10.3 A positron emission tomography (PET) scan shows normal brain activity during sleep. A radioactive isotope that emits positrons is made into a chemical compound that is absorbed by active areas of the brain. The emitted positrons collide with nearby electrons and produce gamma rays that pass through the skull to detectors surrounding the patient's head. A computer uses the detector data to construct the image.

✔ **LEARNING CHECK 10.3** Write a general balanced equation for the nuclear process that occurs during positron emission. How do the atomic numbers of daughter nuclei compare with those of the decaying nucleus?

Certain nuclear changes occur when an electron from outside the nucleus is drawn into the nucleus, where it reacts with a proton and converts it to a neutron. This process, called **electron capture**, is not as common as other decay processes.

electron capture A mode of decay for some unstable nuclei in which an electron from outside the nucleus is drawn into the nucleus, where it combines with a proton to form a neutron.

✔ **LEARNING CHECK 10.4** Write a general balanced equation for the nuclear process that occurs during electron capture. How do the atomic numbers of daughter nuclei compare with those of the decaying nucleus?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 10.3 Writing Balanced Nuclear Equations

Write a balanced nuclear equation for the decay of each of the following. The mode of decay is indicated in parentheses.

a. ${}^{59}_{26}\text{Fe}$ (beta emission), used in diagnosing anemia, bone marrow function

b. ${}^{122}_{53}\text{I}$ (positron emission)

c. ${}^{55}_{26}\text{Fe}$ (electron capture)

d. ${}^{212}_{84}\text{Po}$ (alpha emission)

Solution

In each case, the atomic number of the daughter is obtained by balancing atomic numbers in the equation. The symbol for the daughter is obtained by matching atomic numbers to symbols in the periodic table.

a. ${}^{59}_{26}\text{Fe} \rightarrow {}^{0}_{-1}\beta + {}^{59}_{27}\text{Co}$

b. ${}^{122}_{53}\text{I} \rightarrow {}^{0}_{1}\beta + {}^{122}_{52}\text{Te}$

c. ${}^{55}_{26}\text{Fe} + {}^{0}_{-1}e \rightarrow {}^{55}_{25}\text{Mn}$

d. ${}^{212}_{84}\text{Po} \rightarrow {}^{4}_{2}\alpha + {}^{208}_{82}\text{Pb}$

✔ **LEARNING CHECK 10.5** Write a balanced nuclear equation for the decay of each of the following. The mode of decay is indicated in parentheses.

a. ${}^{50}_{25}\text{Mn}$ (positron emission)

b. ${}^{54}_{25}\text{Mn}$ (electron capture)

c. ${}^{56}_{25}\text{Mn}$ (beta emission)

d. ${}^{224}_{88}\text{Ra}$ (alpha emission)

10.3 Isotope Half-Life

Learning Objective 3 Solve problems using the half-life concept.

Some radioactive isotopes are more stable than others. The more stable isotopes undergo radioactive decay more slowly than the less stable isotopes. The **half-life** of an isotope is used to indicate stability, and it is equal to the time required for one-half (50%) of the atoms of a sample of the isotope to decay. **Table 10.2** contains examples showing the wide range of half-lives that have been determined.

half-life The time required for one-half the unstable nuclei in a sample to undergo radioactive decay.

TABLE 10.2 Examples of Half-Lives

Isotope	Half-Life	Source
${}^{238}_{92}\text{U}$	4.5×10^{9} years	Naturally occurring
${}^{40}_{19}\text{K}$	1.3×10^{9} years	Naturally occurring
${}^{226}_{88}\text{Ra}$	1600 years	Naturally occurring
${}^{14}_{6}\text{C}$	5600 years	Naturally occurring
${}^{239}_{94}\text{Pu}$	24,000 years	Synthetically produced
${}^{90}_{38}\text{Sr}$	28 years	Synthetically produced
${}^{131}_{53}\text{I}$	8 days	Synthetically produced
${}^{24}_{11}\text{Na}$	15 hours	Synthetically produced
${}^{15}_{8}\text{O}$	2 minutes	Synthetically produced
${}^{5}_{3}\text{Li}$	10^{-21} seconds	Synthetically produced

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 10.4 Calculating Half-Lives

Rubidium-84 is used to monitor cardiac output. Another isotope, rubidium-79, decays by positron emission and forms krypton-79, which is a gas. A weighed 100.00 mg sample of solid rubidium-79 was allowed to decay for 42 minutes, then weighed again. Its mass was 25.00 mg. What is the half-life of rubidium-79?

Solution

We assume all the gaseous krypton-79 that was formed escaped into the surrounding air and so was not weighed. In the first half-life, one-half of the original 100.00 mg sample of rubidium would have been lost, so the sample would have a mass of 50.00 mg. During the second half-life, this 50.00 mg sample would again lose half its mass and would be reduced to 25.00 mg. Thus, we can conclude that two half-lives passed during the 42 minutes that elapsed between the weighings. Because two half-lives equal 42 minutes, one half-life equals 21 minutes.

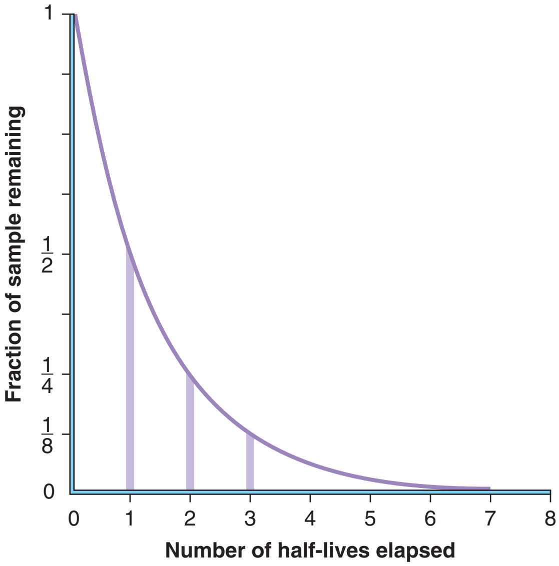
✔ **LEARNING CHECK 10.6** Potassium-38 decays by positron emission to argon-38, a gas. Potassium-38 has a half-life of 7.7 minutes. How long will it take a 200.00 mg sample of potassium-38 to be reduced to 25.00 mg?

Because radioisotopes are continuously decaying, any isotope found in nature must belong to one of three categories. They may have very long half-lives and decay very slowly ($^{238}_{92}U$), they may be daughters produced by the decay of long-lived isotopes ($^{226}_{88}Ra$), or they may result from natural processes such as cosmic-ray bombardment of stable nuclei ($^{14}_{6}C$).

The fraction of original radioactive atoms remaining in a sample after a specific time has passed can be determined from the half-life. After one half-life has passed, $\frac{1}{2}$ the original number have decayed, so $\frac{1}{2}$ remain. During the next half-life, $\frac{1}{2}$ of the remaining $\frac{1}{2}$ decay, so $\frac{1}{4}$ of the original atoms remain. After three half-lives, $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$ of the original atoms remain undecayed (see **Figure 10.4**).

The amount of radiation given off by a sample of radioactive material is proportional to the number of radioactive atoms present in the sample. The amount of radiation given off is called the *activity* of the sample and is measured by devices such as the Geiger–Müller counter described in **Section 10.5**. Data such as the sample fractions shown in **Figure 10.4** are obtained quite easily. For example, suppose a sample gave an initial reading of 120 units of activity, and it took 35 minutes for the reading to drop to 60 units. The reading of 60 units means that the sample contained just half as many radioactive atoms as it contained when the reading was 120 units. Thus, the 35 minutes represents one half-life, and the fraction remaining from the time of the initial measurement is $\frac{1}{2}$.

FIGURE 10.4 A radioactive decay curve (bars give values at 1, 2, and 3 half-lives).



Example 10.5 More Half-Life Calculations

The activity (amount of radiation emitted) of a radioactive substance is measured at 9 a.m. At 5 p.m. the activity is found to be only $\frac{1}{16}$ the original (9 a.m.) value. What is the half-life of the radioactive material?

Solution

Because only $\frac{1}{16}$ the original radioactive material is present, four half-lives have passed: $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{16}$. The time between measurements is 8 hours (9 a.m. to 5 p.m.). Therefore, 8 hours is four half-lives, and the half-life is 2 hours.

✔ **LEARNING CHECK 10.7** Iodine-123 is a radioisotope used to diagnose the function of the thyroid gland. It has a half-life of 13.3 hours. What fraction of a diagnostic dose of iodine-123 would be present in a patient 79.8 hours (a little over 3 days) after it was administered?

10.4 The Health Effects of Radiation

Learning Objective 4 Describe the effects of radiation on health.

You are probably aware of the fact that radiation is hazardous to living organisms. But why? What does radiation do that is so dangerous? The greatest danger to living organisms results from the ability of high-energy or ionizing radiation to knock electrons out of compounds and generate highly reactive particles called **radicals** or **free radicals** in tissue through which the radiation passes. These electron-deficient particles are very reactive. They cause reactions to occur among more stable materials in the cells of living organisms. When these reactions involve genetic materials such as genes and chromosomes, the changes might lead to genetic mutations, cancer, or other serious consequences.

radical or **free radical** An electron-deficient particle that is very reactive.

Long-term exposure to low-level radiation is more likely to cause the problems just described than are short exposures to intense radiation. Short-term intense radiation tends to destroy tissue rapidly in the area exposed and can cause symptoms of so-called **acute radiation syndrome**. Some of these symptoms are given in **Table 10.3**. It is this

acute radiation syndrome The condition associated with and following short-term exposure to intense radiation.

TABLE 10.3 The Effects on Humans of Short-Term, Whole-Body Radiation Exposure

Dose (rems)[a]	Effects
0–25	No detectable clinical effects.
25–100	Slight short-term reduction in number of some blood cells, disabling sickness not common.
100–200	Nausea and fatigue, vomiting if dose is greater than 125 rems, longer-term reduction in number of some blood cells.
200–300	Nausea and vomiting first day of exposure, up to a 2-week latent period followed by appetite loss, general malaise, sore throat, pallor, diarrhea, and moderate emaciation. Recovery in about 3 months unless complicated by infection or injury.
300–600	Nausea, vomiting, and diarrhea in first few hours. Up to a 1-week latent period followed by loss of appetite, fever, and general malaise in the second week, followed by hemorrhage, inflammation of mouth and throat, diarrhea, and emaciation. Some deaths in 2–6 weeks. Eventual death for 50% if exposure is above 450 rems; others recover in about 6 months.
600 or more	Nausea, vomiting, and diarrhea in first few hours. Rapid emaciation and death as early as second week. Eventual death rate of nearly 100%.

[a] The rem, a biological unit of radiation, is defined in **Section 10.5**.

Source: U.S. Atomic Energy Commission.

rapid destruction of tissue that makes relatively intense radiation a useful tool in the treatment of some cancers.

The health hazards presented by radiation make it imperative that exposures be minimized. This is especially true for individuals with occupations that continually present opportunities for exposure. One approach is to absorb radiation by shielding. As shown in **Table 10.4**, alpha and beta rays are the easiest to stop. Gamma radiation and X-rays require the use of very dense materials such as lead to provide protection. If the type of radiation is known, a careful choice of shielding materials can provide effective protection (see **Figure 10.5**).

TABLE 10.4 Penetrating Abilities of Alpha, Beta, and Gamma Rays

Type of Radiation	Depth of Penetration into		
	Dry Air	Tissue	Lead
Alpha	4 cm	0.05 mm	0
Beta[a]	6–300 cm	0.06–4 mm	0.005–0.3 mm
Gamma[b]	400 m	50 cm	300 mm

[a] Depth depends on energy of rays.

[b] Depth listed is that necessary to reduce initial intensity by 10%.

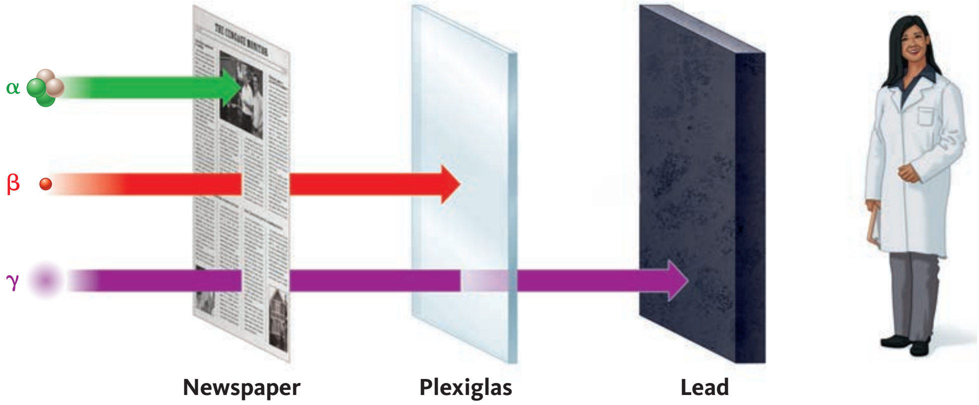


FIGURE 10.5 Penetration of materials by ionizing radiation.

Another protection against radiation is distance. Because radiation spreads in all directions from a source, the amount falling on a given area decreases the farther that area is from the source. Imagine a light bulb at the center of a balloon that is being filled slowly with air. The intensity of light on each square centimeter of the balloon will decrease as the surface of the balloon moves away from the light. It has been shown that the intensity is inversely proportional to the square of the distance of the surface from the radiation source. This **inverse square law of radiation** is true only for radiation traveling in a vacuum, but it gives pretty good results when the radiation travels through air. The law is represented by Equation 10.2, where I_x is the intensity at distance d_x and I_y is the intensity at distance d_y:

inverse square law of radiation A mathematical way of saying that the intensity of radiation is inversely proportional to the square of the distance from the source of the radiation.

$$\frac{I_x}{I_y} = \frac{d_y^2}{d_x^2} \tag{10.2}$$

Example 10.6 Distance and Radiation Intensity

The intensity of radiation is 18.5 units at a distance of 50.0 cm from a source. What is the intensity at a distance of 100.0 cm?

Solution

If $I_x = 18.5$ units and $d_x = 50.0$ cm. Then I_y is wanted at $d_y = 100.0$ cm. Substitution into Equation 10.2 gives

$$\frac{18.5}{I_y} = \frac{(100.0\text{ cm})^2}{(50.0\text{ cm})^2}$$

or

$$I_y = \frac{(50.0\,\cancel{\text{cm}})^2(18.5)}{(100.0\,\cancel{\text{cm}})^2} = 4.63\text{ units}$$

Thus, doubling the distance cuts the intensity to one-fourth the initial intensity.

✔ **LEARNING CHECK 10.8** The intensity of a radioactive source is measured at a distance of 25 feet and equals 10.0 units. What is the intensity 5.0 feet from the source?

IanDagnall Computing/Alamy Stock Photo

FIGURE 10.6 Marie Curie is a towering figure in the history of chemistry and physics. She is most famous for the discovery of the elements polonium and radium. Marie Curie is the only person to win Nobel Prizes in two separate sciences.

10.5 Measurement Units for Radiation

Learning Objective 5 Describe and compare the units used to measure quantities of radiation.

Two methods, physical and biological, are used to describe quantities of radiation. **Physical units** indicate the activity of a source of radiation, typically in terms of the number of nuclei that decay per unit of time. **Biological units** are related to the damage caused by radiation and account for the fact that a given quantity (or number of particles) of one type of radiation does not have the same damaging effect on tissue as the same quantity of another type of radiation.

The curie (see **Figure 10.6**) and the becquerel are physical units. The **curie** is most widely used at the present time and is equal to 3.7×10^{10} nuclear disintegrations per second. One curie (Ci) represents a large unit, so fractions such as the millicurie (mCi), the microcurie (μCi), and the picocurie (pCi) are often used. The **becquerel** (Bq) is a relatively new unit that has achieved little use among U.S. scientists, even though it is smaller and more manageable than the curie. One becquerel is equal to one disintegration per second.

A number of biological units are used, including the roentgen (R), rad (D), gray (Gy), and rem. The **roentgen** is a biological unit used with X-rays or gamma rays. One roentgen is the quantity of radiation that will generate 2.1×10^9 ion pairs in 1 cm^3 of dry air at normal temperature and pressure. The ionization effect of X-rays and gamma rays is greater when the radiation passes through tissue; one roentgen generates about 1.8×10^{12} ion pairs per gram of tissue.

The rad and the gray are biological units used to describe the effects of radiation in terms of the amount of energy transferred from the radiation to the tissue through which it passes. One **rad** transfers 1×10^{-2} J or 2.4×10^{-3} cal of energy to 1 kg of tissue. One **gray**, a larger unit, transfers 1 J per 1 kg of tissue. From a health point of view, the roentgen and rad are essentially equal. One roentgen of X-rays or gamma rays equals 0.96 rad.

The rem is a biological unit devised to account for health differences in various types of radiation. A 1-rad dose of gamma radiation does not produce the same health effects as a 1-rad dose of alpha radiation. An additive unit was needed so that one unit of alpha had the same health effects as one unit of gamma. The devised unit is the rem, which stands for roentgen equivalent in man. One **rem** of any type of radiation has the same health effect as 1 roentgen of gamma rays or X-rays. The advantage of such a unit is that individuals exposed to low levels of various types of radiation have to keep track only of the rems

physical unit of radiation A radiation measurement unit indicating the activity of the source of the radiation; for example, the number of nuclear decays per minute.

biological unit of radiation A radiation measurement unit indicating the damage caused by radiation in living tissue.

curie A physical unit of radiation measurement corresponding to 3.7×10^{10} nuclear disintegrations per second.

becquerel A physical unit of radiation measurement corresponding to one nuclear disintegration per second.

roentgen A biological unit of radiation measurement used with X-rays and gamma rays; the quantity of radiation that generates 2.1×10^9 ion pairs per 1 cm^3 of dry air or 1.8×10^{12} ion pairs per 1 g of tissue.

rad A biological unit of radiation measurement corresponding to the transfer of 1×10^{-2} J or 2.4×10^{-3} cal of energy to 1 kg of tissue.

gray A biological unit of radiation measurement corresponding to the transfer of 1 J of energy to 1 kg of tissue.

rem A biological unit of radiation measurement corresponding to the health effect produced by 1 roentgen of gamma or X-rays, regardless of the type of radiation involved.

HEALTH CONNECTIONS 10.1

Diagnostic Radiation

Throughout our existence, we humans have been continually exposed to radiation from naturally occurring radioisotopes, sunlight, and cosmic rays from outer space. The discovery of X-rays in 1895 by Wilhelm Roentgen contributed to this exposure when X-rays were introduced as a diagnostic tool for patients. Today, X-rays are used in numerous medical and dental diagnostic tests and procedures.

In the early 1970s, X-rays were integrated with computers to create a diagnostic tool called *computed tomography*, or CT scans. In this procedure, the intensity of X-rays after they pass through the body is interpreted using a computer, and the computer results are used to create a cross-sectional image of the part of the body through which the X-rays passed.

In 1946, the property called *nuclear magnetic resonance* was discovered. Today, this property is widely used medically in the diagnostic procedure called *magnetic resonance imaging*, or MRI. During an MRI procedure, the patient is placed in a very strong magnetic field and radiation in the form of powerful radio waves is passed through the patient's body. The energy of the radio waves is absorbed by hydrogen atoms in the body and then re-emitted. The re-emitted radio waves are interpreted by a powerful computer program that then produces cross-sectional images of the body.

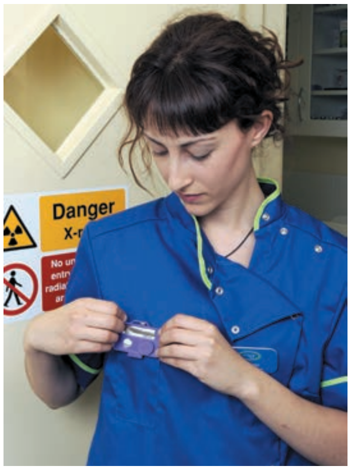
Tyler Olson/Shutterstock.com

Magnetic resonance imaging (MRI) scans enable medical personnel to view soft tissues in detail.

absorbed from each type and add them up to get the total health effect. If other units were used, the number of units from each type of radiation would have to be determined and the health effects calculated for each type. The units used for measuring radiation are summarized in **Table 10.5**, together with relationships among the units.

TABLE 10.5 Units for Measuring Radiation

Unit	Type of Unit	Relationships between Units
Curie (Ci)	Physical	1 Ci = 3.7×10^{10} Bq
Becquerel (Bq)	Physical	1 Bq = 2.7×10^{-11} Ci
Roentgen (R)	Biological	1 R = 0.96 D (tissue)
Rad (D)	Biological	1 D = 1×10^{-2} Gy
Gray (Gy)	Biological	1 Gy = 1×10^{2} D
Rem	Biological	1 rem = 1 R X-ray or gamma ray in health effect



Public Health England/Science Source

FIGURE 10.7 Film badges provide a convenient way to monitor the total amount of radiation received during a specific time period.

Radiation can be detected in a number of ways. Film badges are commonly used by people working in environments where they might be exposed to radiation. The badges contain photographic film that becomes exposed when subjected to radiation. The extent of exposure of the film increases with the amount of radiation. The film is developed after a specific amount of time, and the degree of exposure indicates the radiation dose that has been absorbed during that time (see **Figure 10.7**).

Radiation causes certain substances, called phosphors, to give off visible light. The light appears as brief flashes when radiation strikes a surface coated with a thin layer of phosphors. The number of flashes (called *scintillations*) per unit time is proportional to the amount of radiation striking the surface. A device that employs this approach is called a **scintillation counter**.

scintillation counter A radiation-detection device operating on the principle that phosphors give off light when struck by radiation.

A third type of detector, called a **Geiger–Müller tube**, is based on the fact that electricity is conducted through a gas that contains charged particles. A Geiger–Müller tube is represented in **Figure 10.8**. The tube essentially consists of two electrodes charged to high voltages of opposite sign. The tube is filled with a gas at very low pressure. When radiation passes through the tube, it creates a path of charged particles (ions) by knocking electrons off gas molecules. They conduct a brief pulse of current between the electrodes. This brief current is amplified and triggers a counting circuit to record one "count." The number of counts per unit time is proportional to the amount of radiation passing through the Geiger–Müller tube.

Geiger–Müller tube A radiation-detection device operating on the principle that ions form when radiation passes through a tube filled with low-pressure gas.

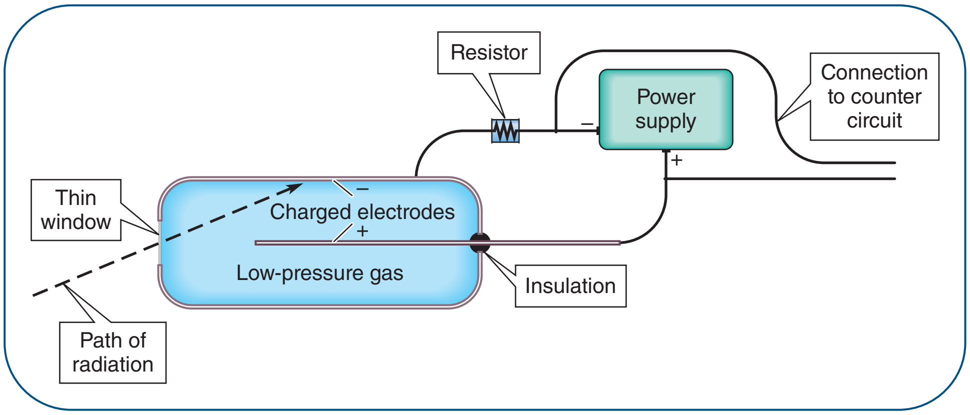


FIGURE 10.8 A cross section of a detection tube used in Geiger–Müller counters.

10.6 Medical Uses of Radioisotopes

Learning Objective 6 Describe, with examples, medical uses of radioisotopes.

Chemically, radioisotopes undergo the same reactions as nonradioactive isotopes of the same element. For example, radioactive iodine-123 is absorbed by the thyroid gland and used to produce the hormone thyroxine just as if it were ordinary nonradioactive iodine. This characteristic, together with the fact that the location of radioisotopes in the body can be readily detected, makes them useful for diagnostic and therapeutic medical applications. In diagnostic applications, radioisotopes are used as **tracers**, whose progress through the body or localization in specific organs can be followed.

tracer A radioisotope used medically because its progress through the body or localization in specific organs can be followed.

To minimize the risks to patients from exposure to radiation, radioisotopes used as diagnostic tracers should have as many of the following characteristics as possible:

1. Tracers should have short half-lives so they will decay while the diagnosis is being done but will give off as little radiation as possible after the diagnostic procedure is completed.
2. The daughter produced by the decaying radioisotope should be nontoxic and give off little or no radiation of its own. Ideally, it will be stable.
3. The radioisotope should have a long enough half-life to allow it to be prepared and administered conveniently.
4. The radiation given off by the radioisotope should be penetrating gamma rays, if possible, to ensure that they can be detected readily by detectors located outside the body.
5. The radioisotope should have chemical properties that make it possible for the tissue being studied to either concentrate it in diseased areas and form a **hot spot** or essentially reject it from diseased areas to form a **cold spot**.

hot spot Tissue in which a radioactive tracer concentrates.

cold spot Tissue from which a radioactive tracer is excluded or rejected.

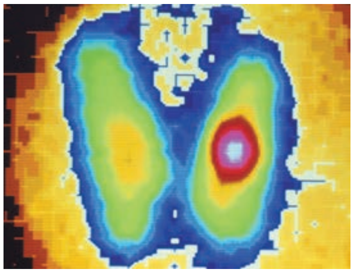

Centre Jean Perrin/Science Source

FIGURE 10.9 A thyroid scan produced after the administration of a radioactive iodine isotope. Is either a hot spot or a cold spot present?

Iodine-123 is used diagnostically to determine whether a thyroid gland is properly functioning. As mentioned earlier, the thyroid gland concentrates iodine and uses it in the production of thyroxine, an iodine-containing hormone. Iodine is an excellent tracer to use because the thyroid is the only user of iodine in the body. Iodine-123 is a good tracer because it is a gamma-emitter with a half-life of 13.3 hours. Iodine-131 is also radioactive and has a short half-life (8 days), but it emits gamma and beta radiation. The beta radiation cannot penetrate through the tissue to be detected diagnostically and therefore is simply an added radiation risk to the patient. For this reason, iodine-123 is preferred. An overactive thyroid absorbs more iodine and forms a hot spot, whereas an underactive or nonactive gland absorbs less iodine and may show a cold spot on a thyroid scan (see **Figure 10.9**).

Radioisotopes administered internally for therapeutic use should ideally have the following characteristics:

1. The radioisotope should emit less penetrating alpha or beta radiation to restrict the extent of damage to the desired tissue.
2. The half-life should be long enough to allow sufficient time for the desired therapy to be accomplished.
3. The decay products should be nontoxic and give off little or no radiation.
4. The target tissue should concentrate the radioisotope to restrict the radiation damage to the target tissue.

Iodine-131 is used therapeutically to treat thyroid cancer and hyperthyroidism. The primary advantage of this radioisotope is the ability of thyroid tissue to absorb it and localize its effects.

Until the mid-1950s, when improvements in the generation of penetrating X-rays made them the therapy of choice, cobalt-60 was widely used to treat cancer. This radioisotope emits beta and gamma radiation and has a half-life of 5.3 years. When used therapeutically today, a sample of cobalt-60 is placed in a heavy lead container with a window aimed at the cancerous site. The beam of gamma radiation that exits through the window is focused on a small area of the body where the tumor is located. **Table 10.6** contains other examples of radioisotopes used diagnostically and therapeutically.

TABLE 10.6 Examples of Medically Useful Radioisotopes

Isotope	Emission	Half-Life	Applications
$^{3}_{1}H$	Beta	12.3 years	To measure water content of the body
$^{32}_{15}P$	Beta	14.3 days	Detection of tumors, treatment of a form of leukemia
$^{51}_{24}Cr$	Gamma	27.8 days	Diagnosis: size and shape of spleen, gastrointestinal disorders
$^{59}_{26}Fe$	Beta	45.1 days	Diagnosis: anemia, bone marrow function
$^{60}_{27}Co$	Beta, gamma	5.3 years	Therapy: cancer treatment
$^{67}_{31}Ga$	Gamma	78.1 hours	Diagnosis: various tumors
$^{75}_{34}Se$	Beta	120.4 days	Diagnosis: pancreatic scan
$^{81}_{36}Kr$	Gamma	2.1×10^5 years	Diagnosis: lung ventilation scan
$^{85}_{38}Sr$	Gamma	64 days	Diagnosis: bone scan
$^{99}_{43}Tc$	Gamma	6 hours	Diagnosis: brain, liver, kidney, bone, and heart muscle scans
$^{123}_{53}I$	Gamma	13.3 hours	Diagnosis: thyroid cancer
$^{131}_{53}I$	Beta, gamma	8.1 days	Diagnosis and treatment: thyroid cancer
$^{197}_{80}Hg$	Gamma	65 hours	Diagnosis: kidney scan

10.7 Nonmedical Uses of Radioisotopes

Learning Objective 7 Describe, with examples, nonmedical uses of radioisotopes.

The study of the photosynthetic process in plants has been made much easier because of the use of radioactive carbon-14 as a tracer. The overall photosynthetic process is represented by Equation 10.3:

$$6CO_2(g) + 6H_2O(\ell) \xrightarrow{hv} C_6H_{12}O_6(aq) + 6O_2(g) \qquad (10.3)$$

However, the conversion of water (H_2O) and carbon dioxide (CO_2) into carbohydrates ($C_6H_{12}O_6$) involves numerous chemical reactions and carbon-containing intermediate compounds. By using CO_2 that contains radioactive carbon-14, scientists have been able to follow the chemical path of CO_2 through the various intermediate compounds.

Interesting uses for radioactive tracers are found in industry. In the petroleum industry, for example, radioisotopes are used in pipelines to indicate the boundary between different products moving through the lines (see **Figure 10.10**). In another application, tracer added to fluids moving in pipes makes it easy to detect leaks. Also, the effectiveness of lubricants has been studied by the use of radioactive metal isotopes as components of metal parts; as the metal part wears, the isotope shows up in the lubricant, and the amount of wear can be determined.

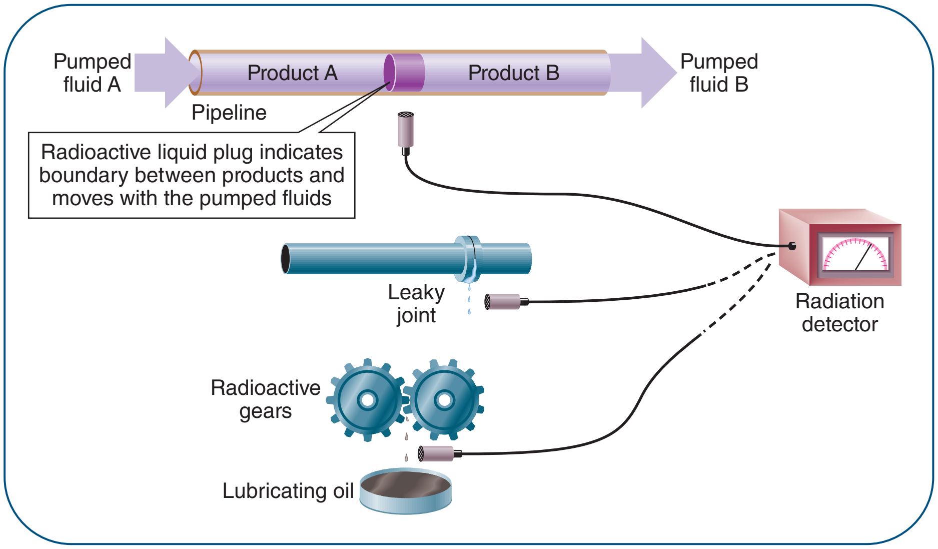


FIGURE 10.10 Radioactive tracers used in industry.

Radioisotopes are also useful in forms other than tracers. The thickness of manufactured materials, such as metal foils or sheets, can be determined continuously by the use of a radioisotope. The amount of radiation that penetrates the material to the detector is related to the thickness of the material.

An interesting application of radioisotopes involves the use of naturally occurring radioactive materials to determine the ages of artifacts and rocks. Perhaps the most widely known example of **radioactive dating** is the use of carbon-14, which is produced in the atmosphere when cosmic-ray neutrons strike nitrogen nuclei. The equation for the reaction is

radioactive dating A process for determining the age of artifacts and rocks, based on the amount and half-life of radioisotopes contained in the object.

$$^{14}_{7}N + ^{1}_{0}n \rightarrow ^{14}_{6}C + ^{1}_{1}p \qquad (10.4)$$

The resulting $^{14}_{6}C$ is converted to carbon dioxide $^{14}_{6}CO_2$ through a chemical reaction with oxygen. In this form, the radioactive carbon is absorbed by plants and converted into cellulose or other carbohydrates during photosynthesis. As long as the plant lives, it takes in $^{14}_{6}CO_2$. As a result, an equilibrium is established in which the plant contains the same fraction of carbon-14 as the surrounding air. Thus, as long as the plant lives, a constant fraction of the total carbon present is carbon-14. When the plant dies, $^{14}_{6}CO_2$ intake stops,

HEALTH CONNECTIONS **10.2**

Check the Radon Level in Your Home

Substances that are chemically unreactive are generally not thought to be dangerous to one's health. However, radon, a colorless, odorless, chemically inert noble gas, is considered to be a serious health risk because it is radioactive. It is believed to be the leading cause of lung cancer among nonsmokers. It has been estimated by U.S. officials that up to 8% of the annual lung cancer deaths in the United States can be attributed to indoor exposure to radon-222.

Radon-222 is formed during a multistep process in which naturally occurring uranium-238 decays to stable lead-206. During one step of the process, radium-226, with a half-life of 1600 years, emits alpha and gamma radiation to produce radon-222:

$$^{226}_{88}\text{Ra} \rightarrow {}^{4}_{2}\alpha + {}^{222}_{86}\text{Rn} + \gamma$$

Radon-222, with a half-life of 4 days, is produced in rocks and soil that contain even minute amounts of uranium-238. Because it is a gas, radon migrates readily from the soil into the surrounding air. It seeps into houses and other buildings through openings around pipes, and through cracks in basement floors and walls.

The hazards associated with breathing radon-222 come not only from the alpha radiation emitted as the radon decays but also from the daughter products of that decay. None of these decay products are gases, but all are radioactive. Because they are not gases, they are not easily exhaled and can become lodged in the lungs, where their radiation can cause serious damage.

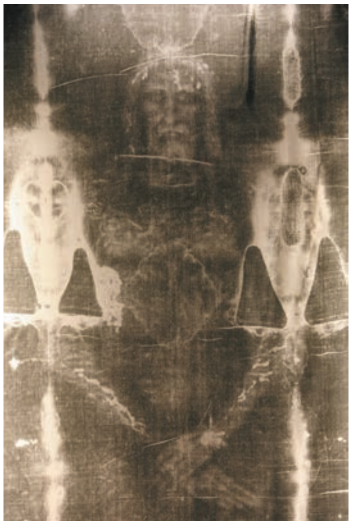
It is quite easy and relatively inexpensive to test for radon in a home, and homes built in locations where the gas has been identified as a problem should be tested.

Pollenex
Radon Analyst
Radon Test Kit
In-Home Detector
Express Laboratory Analysis

© Cengage Learning/Charles D. Winters

Radon detectors are available for home use.

and the fractional amount of carbon-14 begins to decrease. From a measurement of this amount in, say, a wooden object, and a knowledge of the half-life of carbon-14 (5600 years), it is possible to calculate the age of the object—how long since the tree was cut down to make the object. An object containing only about one-eighth as much carbon-14 as a fresh wood sample from a living tree would be about three half-lives, or 16,800 years old.



P Deliss/The Image Bank Unreleased/Getty Images

FIGURE 10.11 The Shroud of Turin, a linen cloth with an apparent human imprint, has been dated using carbon-14 analysis to a range of 1260–1390 C.E. The results showed that the linen is a medieval fabric.

This method is limited to objects less than about 50,000 years old because of difficulties in measuring the small amount of carbon-14 present (see **Figure 10.11**). For this reason, other dating methods have been developed. One method involves potassium-40 and argon-40. The half-life of potassium-40, which absorbs one of its own inner electrons to produce argon-40, is 1.3×10^9 years. By determining the amount of argon-40 in a potassium-containing mineral, it is possible to estimate the age of the mineral. The equation for the reaction is

$$^{40}_{19}\text{K} + {}^{0}_{-1}\text{e} \rightarrow {}^{40}_{18}\text{Ar} \qquad (10.5)$$

10.8 Induced Nuclear Reactions

Learning Objective 8 Show that you understand the concept of induced nuclear reactions.

Before 1934, the study of radioactivity was limited to reactions of the relatively few radioisotopes found in nature. In that year, Irene and Frederic Joliot-Curie, French physical chemists (see **Figure 10.12**), found that radioactivity could be induced in nonradioactive nuclei by bombarding them with small, subatomic particles. They produced an artificial radioactive isotope, nitrogen-13, by bombarding boron-10 with alpha particles from a natural radioisotope:

$$^{10}_{5}\text{B} + {}^{4}_{2}\alpha \rightarrow {}^{13}_{7}\text{N} + {}^{1}_{0}\text{n} \qquad (10.6)$$

Notice that a neutron, ${}_{0}^{1}n$, is produced in addition to ${}_{7}^{13}\mathrm{N}$. Fifteen years earlier, British physicist Ernest Rutherford had used a similar reaction to produce nonradioactive oxygen-17 from nitrogen-14. A small particle, a proton, was produced in addition to oxygen-17:

$$ {}_{7}^{14}\mathrm{N} + {}_{2}^{4}\alpha \rightarrow {}_{8}^{17}\mathrm{O} + {}_{1}^{1}\mathrm{p} \tag{10.7} $$

A great deal of research has been done since these first experiments were performed, and today it is known that a variety of nuclear reactions can be induced by bombarding either stable or naturally radioactive nuclei with high-energy particles. These artificially induced reactions may lead to one of four results. The first possibility is that the bombarded nucleus may be changed into a different nucleus that is stable. A second possibility is that a new nucleus may be formed that is unstable and undergoes radioactive decay. The other two possibilities are that nuclear fission or nuclear fusion will take place. These are discussed in more detail in **Section 10.9**. The result of bombardment depends on the kind of nuclei bombarded and the nature and energy of the bombarding particles.

Charged or uncharged particles may be used to bombard nuclei, and each type presents unique problems to overcome. It is believed that a bombarding particle will be drawn into the nucleus of an atom by strong nuclear forces if it can get to within 10^{-12} cm of the nucleus. Neutrons are captured readily if their speeds are reduced enough to allow the nuclear forces to work. Neutrons are slowed by passing them through materials known as **moderators**. Graphite is an example of a neutron moderator. Charged particles present a different problem. If they are negatively charged (${}_{-1}^{0}\beta$), they are repelled by the electron cloud around the nucleus; for a reaction to take place, they must have sufficient energy to overcome this repulsion. Similarly, positive particles must be energetic enough to overcome repulsion by the positively charged nucleus.

Neutrons for bombardment reactions are obtained from other nuclear reactions and, together with proper moderators, are used as they come from the sources. Charged particles are obtained from radioactive materials or from ionization reactions. For example, alpha particles are produced by an ionization reaction in which the two electrons are removed from helium atoms. These charged particles are generally accelerated to high speeds (and energies) before bombarding the intended target nuclei. Two types of particle accelerators, cyclic and linear, are used. The **cyclotron**, one type of cyclic accelerator, is represented in **Figure 10.13**.

The charged particles to be accelerated enter the evacuated chamber at the center of the cyclotron and, because of the magnetic field, move in a circular path towards the gap

ullstein bild Dtl./Getty Images

FIGURE 10.12 Irene Joliot-Curie was a French chemist and physicist. Jointly with her husband, Frederic, she was awarded the Nobel Prize in chemistry in 1935 for their discovery of induced radioactivity.

moderators Materials capable of slowing down neutrons that pass through them.

cyclotron A cyclic particle accelerator that works by changing electrical polarities as charged particles cross a gap. The particles are kept moving in a spiral path by a strong magnetic field.

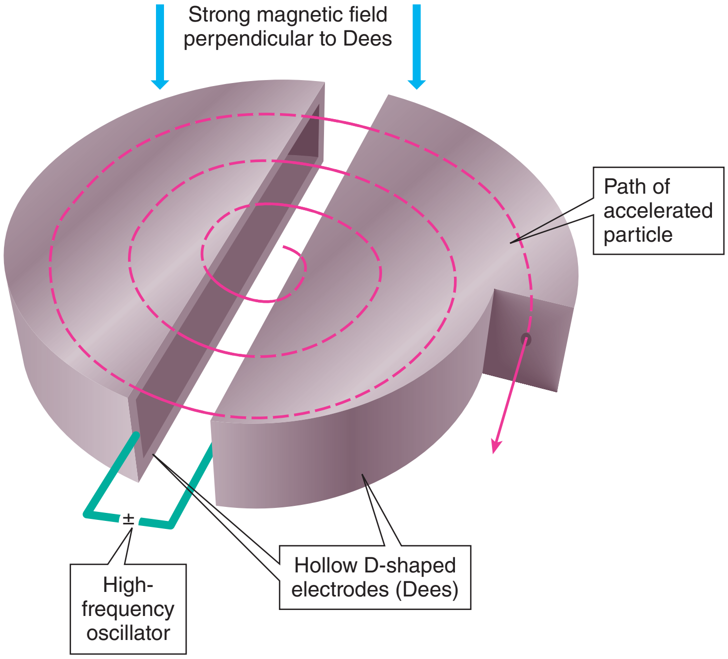

Strong magnetic field perpendicular to Dees
Path of accelerated particle
±
High-frequency oscillator
Hollow D-shaped electrodes (Dees)

FIGURE 10.13 The cyclotron. Early versions of the cyclotron were about the size of a dinner plate.

between the hollow D-shaped electrodes (Dees). Just as the particles reach the gap, the electrical charge on the Dees is adjusted so the particles are repelled by the Dee they are leaving and attracted to the other one. The particles then coast inside the Dee until they again reach a gap, at which point the charges are again adjusted to cause acceleration. This process continues, and the particles are accelerated each time they pass through the gap. As the speed and energy of the particles increase, so does the radius of their circular path, until they finally leave the Dees and strike the target.

linear accelerator A particle accelerator that works by changing electrical polarities as charged particles cross gaps between segments of a long tube.

In a **linear accelerator**, the particles are accelerated through a series of axially aligned, charged tubes located in an evacuated chamber (see **Figure 10.14**). Each time a particle passes through a gap and goes from one tube to another, it is accelerated in the same way as particles passing between the Dees of a cyclotron. To make the particle accelerate, the charges on the tubes are reversed at the proper times. The tubes get successively longer to allow the particles the same residence or coasting time as they move towards the end at ever-increasing speeds. After acceleration, the particles exit and strike the target.

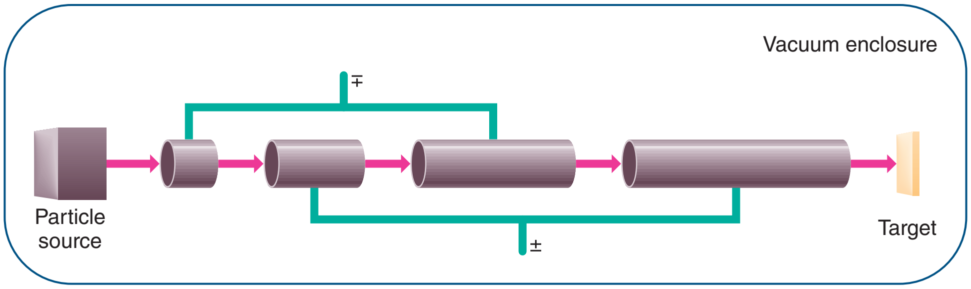


FIGURE 10.14 A linear particle accelerator.

One of the most interesting results of bombardment is the creation of completely new elements. Four of these elements, produced between 1937 and 1941, filled gaps in the periodic table for which no naturally occurring element had been found. These four are technetium (Tc, number 43), promethium (Pm, number 61), astatine (At, number 85), and francium (Fr, number 87). The equations for the reactions for their production are:

$$^{96}_{42}\text{Mo} + {}^{2}_{1}\text{H} \rightarrow {}^{1}_{0}\text{n} + {}^{97}_{43}\text{Tc (half-life: } 2.6 \times 10^{6} \text{ years)} \quad (10.8)$$

$$^{142}_{60}\text{Nd} + {}^{1}_{0}\text{n} \rightarrow {}^{0}_{-1}\beta + {}^{143}_{61}\text{Pm (half-life: 265 days)} \quad (10.9)$$

$$^{209}_{83}\text{Bi} + {}^{4}_{2}\alpha \rightarrow 3{}^{1}_{0}\text{n} + {}^{210}_{85}\text{At (half-life: 8.3 hours)} \quad (10.10)$$

$$^{230}_{90}\text{Th} + {}^{1}_{1}\text{p} \rightarrow 2{}^{4}_{2}\alpha + {}^{223}_{87}\text{Fr (half-life: 22 minutes)} \quad (10.11)$$

transuranium elements Synthetic elements with atomic numbers greater than that of uranium.

Synthetic elements heavier than uranium, the heaviest naturally occurring element, have also been produced. All these elements, called **transuranium elements**, are radioactive. The first, neptunium (Np, number 93), was produced in 1940; since then at least 25 more (numbers 94 through 118) have been synthesized.

Significant quantities of only a few of these elements have been produced. Plutonium is synthesized in quantities large enough to make it available for use in atomic weapons and reactors. In 1968 the entire world's supply of californium (10^{-4} g) was gathered and made into a target for bombardment by heavy, accelerated particles. These experiments led to the discovery of several elements heavier than californium. Usually, the amounts of the new elements produced are extremely small—sometimes only hundreds of atoms. When the half-life is short, this small amount quickly disappears. Thus, these elements have to be identified not by chemical properties but by the use of instruments that analyze the characteristic radiation emitted by each new element.

Example 10.7 Writing Equations for Nuclear Reactions

An isotope of gallium (Ga) useful in medical diagnostic work is formed when zinc-66 is bombarded with accelerated protons. Write the equation for this nuclear reaction and determine what isotope of gallium is produced.

Solution

The equation for the reaction is written

$$ {}^{66}_{30}\mathrm{Zn} + {}^{1}_{1}\mathrm{p} \rightarrow ? $$

where the product is to be determined. By balancing the mass numbers and atomic numbers, we see that the product has a mass number of 67 and an atomic number of 31. Reference to the periodic table shows element number 31 to be gallium, Ga. Therefore, the isotope produced is gallium-67, and the equation for the reaction is:

$$ {}^{66}_{30}\mathrm{Zn} + {}^{1}_{1}\mathrm{p} \rightarrow {}^{67}_{31}\mathrm{Ga} $$

✔ **LEARNING CHECK 10.9** When manganese-55 is bombarded by protons, a neutron is one product. Write the equation for the process and identify the other product.

10.9 Nuclear Energy

Learning Objective 9 Describe the differences between nuclear fission and nuclear fusion reactions.

In 1903, Ernest Rutherford and Frederick Soddy made observations that led them to conclude that the nuclei of all atoms, not just radioactive ones, must contain large quantities of energy. However, the form it took and the means for releasing it remained a mystery. In 1905, Albert Einstein, who was then working as a patent clerk, provided a partial answer. According to his theory of relativity, matter and energy were equivalent and one could be converted into the other. This fact was expressed in his now-famous equation,

$$ E = mc^2 \tag{10.12} $$

According to his equation, a small amount of mass, m, would, upon conversion, yield a huge amount of energy, E. The amount of energy liberated is huge because of the size of the multiplier c^2, the velocity of light squared. The velocity of light is a very large number (3.0×10^8 m/s, or 1.9×10^5 mi/s). The verification of Einstein's theory was not made until 1939, when the work of Otto Hahn, Lise Meitner (see **Figure 10.15**), Fritz Strassman, and Enrico Fermi led to the discovery of **nuclear fission**. Attempts to produce new heavier transuranium elements by bombarding uranium-235 with neutrons led instead to the production of elements much less massive than uranium-235. The uranium-235 nuclei had undergone fission and split into smaller fragments. In the process, a small amount of matter was converted into energy, just as Einstein had predicted.

GL Archive/Alamy Stock Photo

FIGURE 10.15 Lise Meitner was an Austrian–Swedish physicist and part of a team that discovered nuclear fission—a term she coined.

nuclear fission A process in which large nuclei split into smaller, approximately equal-sized nuclei when bombarded by neutrons.

Today, we know that uranium-235 is the only naturally occurring isotope that will undergo fission, and a number of different products can result. Equations 10.13–10.16 represent some of the numerous fission reactions that can occur.

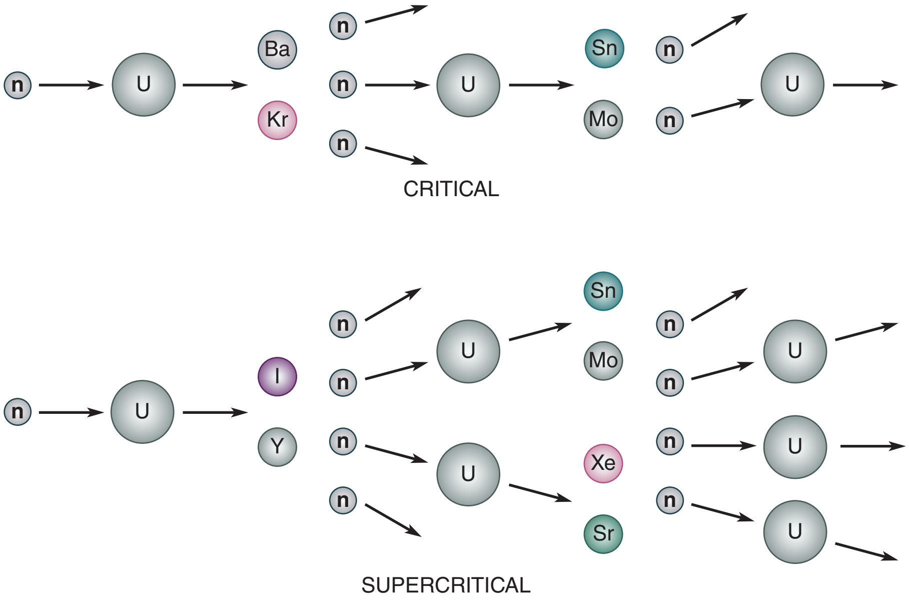
$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \begin{array}{ll} \nearrow {}^{135}_{53}\mathrm{I} + {}^{97}_{39}\mathrm{Y} + 4{}^{1}_{0}\mathrm{n} & (10.13) \\ \rightarrow {}^{139}_{56}\mathrm{Ba} + {}^{94}_{36}\mathrm{Kr} + 3{}^{1}_{0}\mathrm{n} & (10.14) \\ \rightarrow {}^{102}_{42}\mathrm{Mo} + {}^{132}_{50}\mathrm{Sn} + 2{}^{1}_{0}\mathrm{n} & (10.15) \\ \searrow {}^{139}_{54}\mathrm{Xe} + {}^{95}_{38}\mathrm{Sr} + 2{}^{1}_{0}\mathrm{n} & (10.16) \end{array} $$

For every uranium-235 nucleus undergoing fission, more than one neutron is generated, which opens up the possibility for a chain reaction to take place. If only one of the neutrons produced each time reacts with another uranium-235 nucleus, the process will become a **chain reaction** that continues at a constant rate. If more than one of the neutrons generated per fission reaction produces another reaction, the process becomes an **expanding** or **branching chain reaction** that leads to an explosion. A constant-rate chain reaction is

chain reaction A nuclear reaction in which the products of one reaction cause a repeat of the reaction to take place. In the case of uranium fission, neutrons from fission reactions cause other fission reactions to occur.

expanding or **branching chain reaction** A reaction in which the products of one reaction cause more than one more reaction to occur.

FIGURE 10.16 Nuclear chain reactions.


n
U
Ba
Kr
n
n
n
U
Sn
Mo
n
n
U
CRITICAL
n
U
I
Y
n
n
n
n
U
U
Sn
Mo
Xe
Sr
n
n
n
n
U
U
U
U
SUPERCRITICAL

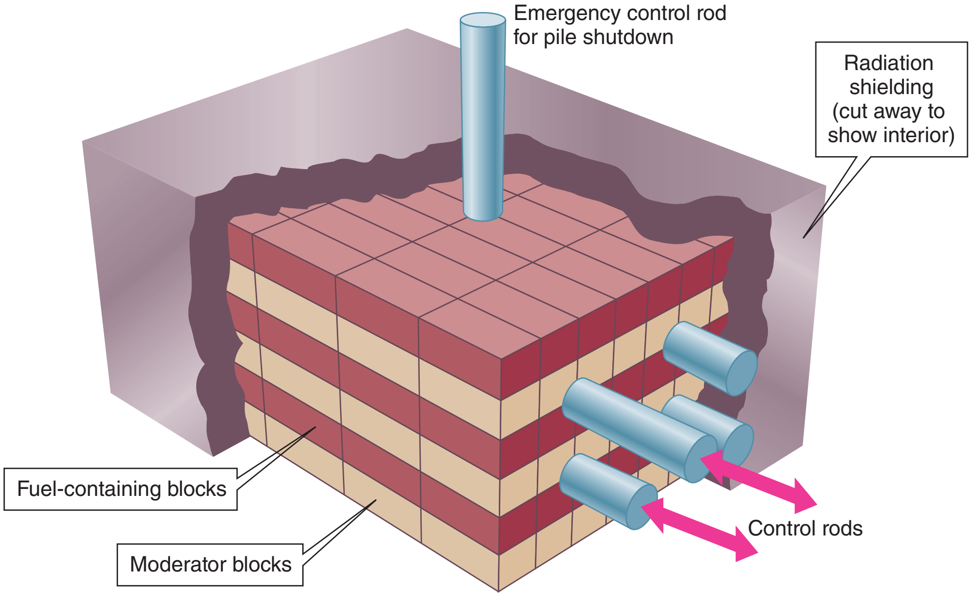
critical reaction A constant-rate chain reaction.

supercritical reaction A branching chain reaction.

called a **critical reaction**. A branching chain reaction that will lead to an explosion is called **supercritical** (see **Figure 10.16**).

History's first critical chain reaction was carried out in an atomic pile, which was literally a stack or pile of uranium-containing graphite blocks and blocks of pure graphite that served as a neutron moderator (see **Figure 10.17**). The pile was constructed in a squash court beneath the stands of an athletic fieldhouse at the University of Chicago, and the experiments were carried out by a team of scientists led by Italian physicist Enrico Fermi. In December 1942, the team observed that nuclear reactions in the pile had become self-sustaining, or critical. The control rods, composed of strong neutron absorbers, were pushed into the pile to stop the reaction.

FIGURE 10.17 An atomic pile, the world's first nuclear reactor.


Emergency control rod for pile shutdown
Radiation shielding (cut away to show interior)
Fuel-containing blocks
Moderator blocks
Control rods

Once it had been demonstrated that uranium-235 would undergo self-sustaining fission, the construction of an atomic bomb was fairly simple in principle, but it depended on the concept of critical mass. Neutrons released inside a small piece of fissionable material might escape to the outside before they collide with and split another atom. If the majority of neutrons are lost this way, a chain reaction will not take place. However, as the size of

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

the piece of fissionable material is increased, the chance for neutrons to escape without hitting other atoms decreases. The amount of fissionable material needed to cause a critical reaction to occur is the **critical mass**. The amount needed to cause a branching chain reaction and explosion to occur is called a **supercritical mass**.

critical mass The minimum amount of fissionable material needed to sustain a critical chain reaction at a constant rate.

supercritical mass The minimum amount of fissionable material that must be present to cause a branching chain reaction to occur.

During World War II, one major difficulty encountered in building a nuclear bomb was the size of the device needed to bring together subcritical masses to form a supercritical mass. Any bomb used in combat would have to fit into a B-29, the largest bomber available at the time, and could not be heavier than the load capacity of the airplane. The configurations of the first two devices actually used are represented in **Figure 10.18**. The spherical configuration resulted in a short, wide bomb, while the tubular configuration gave rise to a long, narrow bomb. In each configuration, explosive charges were used to drive subcritical masses together to form a supercritical mass. These nuclear bombs were the first applications of the concepts of subcritical and supercritical mass.

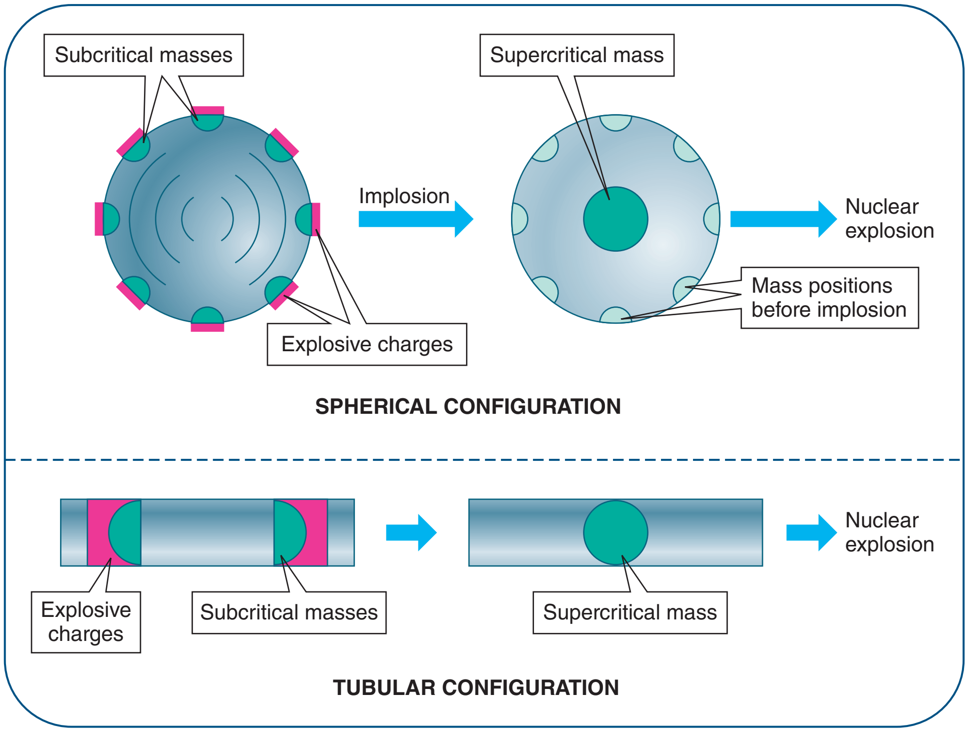


FIGURE 10.18 Configurations used in fission-type nuclear bombs.

On August 6, 1945, the United States became the first nation to use a nuclear weapon in combat. This bomb used a tubular configuration. Approximately 70,000 inhabitants of Hiroshima, Japan, were killed in the explosion; an equal number were seriously injured. A few days later a second bomb, with a spherical configuration, was dropped on the city of Nagasaki. The casualty figures were similar, and World War II came to an end. The Nagasaki bomb was made of plutonium, an artificial fissionable material produced in atomic piles by breeding reactions.

A **breeder reaction** is an induced reaction in which the product nuclei undergo fission reactions. The plutonium used in the Nagasaki bomb was made by bombarding uranium-238 with neutrons in the first atomic pile. Uranium-238 is the most abundant isotope of uranium found in nature, but it will not undergo fission, as will the much less abundant uranium-235. However, uranium-238 reacts as follows when placed in a neutron-rich environment.

breeder reaction A nuclear reaction in which isotopes that will not undergo spontaneous fission are changed into isotopes that will.

$$^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{239}_{92}\text{U} \qquad (10.17)$$

$$^{239}_{92}\text{U} \rightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}\beta \qquad (10.18)$$

$$^{239}_{93}\text{Np} \rightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\beta \qquad (10.19)$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The plutonium-239 will undergo fission and, when collected into a supercritical mass, will cause an explosion. Reactions such as 10.17–10.19 are called breeding reactions because a fissionable material is “bred” from a nonfissionable material.

Curiosity about the seemingly unlimited energy supply of the stars (especially the sun) eventually led scientists to an understanding of a second nuclear process that releases vast amounts of energy. In 1920, Sir Arthur Eddington suggested that the energy of the stars is a by-product of a reaction in which hydrogen is changed into helium. This was followed in 1929 by the concept of a **thermonuclear reaction**, a nuclear reaction that is started by very high temperatures. According to this idea, at high temperatures the nuclei of very lightweight elements will combine to form nuclei of heavier elements, and in the process some mass is converted into energy. This idea was consistent with Eddington’s suggestion that hydrogen is converted to helium in the sun and other stars. It was not until nuclear fission reactions became available that high enough temperatures could be achieved to test the theory of **nuclear fusion**. The theory proved to be correct, and today most nuclear weapons in the world are based on fusion reactions.

thermonuclear reaction A nuclear fusion reaction that requires a very high temperature to start.

nuclear fusion A process in which small nuclei combine or fuse to form larger nuclei.

The fusion reactions responsible for the energy output of the sun (see **Figure 10.19**) are thought to be

$$2{}^{1}_{1}\text{H} \rightarrow {}^{2}_{1}\text{H} + {}^{0}_{1}\beta \tag{10.20}$$

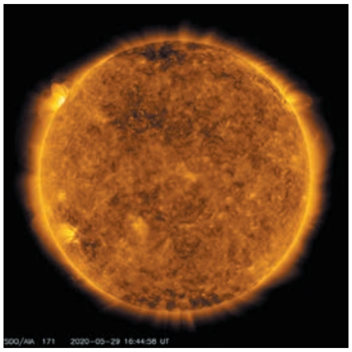
$${}^{1}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + \gamma \tag{10.21}$$

$${}^{3}_{2}\text{He} + {}^{3}_{2}\text{He} \rightarrow {}^{4}_{2}\text{He} + 2{}^{1}_{1}\text{H} \tag{10.22}$$

The net overall reaction is

$$4{}^{1}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + 2{}^{0}_{1}\beta + 2\gamma \tag{10.23}$$

which is what Eddington proposed; hydrogen (${}^{1}_{1}\text{H}$) is converted to helium (${}^{4}_{2}\text{He}$).



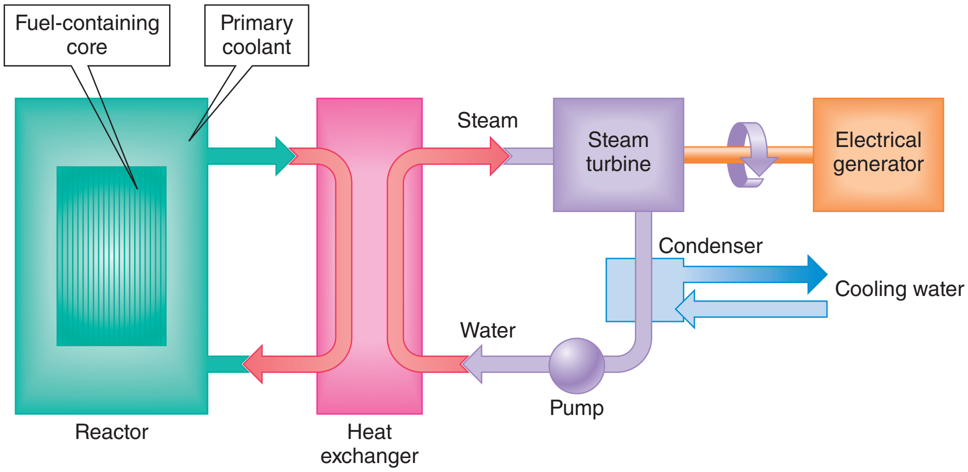
Joy Ng/Solar Dynamics Observatory/NASA

FIGURE 10.19 The sun generates its energy by nuclear fusion of hydrogen nuclei into helium. It is estimated that the sun makes 600 million metric tons of helium each second.

A goal of many of the early developers of nuclear energy was to harness it and make it a virtually unlimited source of useful energy. Today, that goal has been partially achieved. Fission reactors generate a small percentage of the electricity used in the world, and researchers are making progress in their attempts to harness fusion reactions.

The essential components of a fission-powered generating plant are shown in **Figure 10.20**. The use of nuclear power plants has created much controversy. The plants release large amounts of waste heat and thus cause thermal pollution of natural waters. In addition, radioactive wastes create disposal problems—where do you dump radioactive materials that will be a health hazard for thousands of years? Electricity consumers and producers have lost some of their confidence in the safety of nuclear power plants as a result of accidents such as the well-known incidents at Three-Mile Island (1979), Chernobyl (1986), and Fukushima (2011). Another problem is the relatively short supply of fissionable uranium-235. Breeder reactors could solve this problem, since they can convert abundant

FIGURE 10.20 Components of a nuclear electricity power plant.



supplies of uranium-238 and thorium-232 into fissionable fuels, but the breeder reactor program in the United States is at a standstill. As a result of these factors, the future of fission power generation is uncertain at the present time.

In principle, fusion reactors can be used as controlled energy sources just as fission reactors are. Fusion reactors would have many advantages over fission reactors. The deuterium fuel (hydrogen-2) is readily available since it is a minor constituent of all water on Earth, no significant amounts of radioactive wastes would be produced during operation, and the possibility of a serious accident is much smaller. Unfortunately, the feasibility of fusion reactors has not yet been established, although scientists are getting closer through continuing research.

Health Career Description

NUCLEAR MEDICINE TECHNOLOGIST

According to the International Atomic Energy Agency (IAEA), "Radiopharmaceuticals are radioisotopes bound to biological molecules able to target specific organs, tissues or cells within the human body. These radioactive drugs can be used for the diagnosis and, increasingly, for the therapy of diseases."

The nuclear medicine technologist is a health care professional who prepares and administers these specialized medications. Nuclear medicine technologists may also operate computed tomography (CT) and magnetic resonance imaging (MRI) scanners. This field combines, patient care, imaging, computer science, physics, chemistry, and mathematics.

The website explorehealthcareers.org lists the nuclear medicine technologist's responsibilities as:

- Putting the patient at ease, obtaining pertinent history, describing the procedure and answering the patient's questions.
- Administering radiopharmaceuticals and medications for patient imaging and therapeutic procedures.
- Monitoring the patient's physical condition during the course of the procedure.
- Processing data and enhancing digital images using advanced computer technology.
- Providing images, data analysis and patient information for diagnostic interpretation or therapeutic procedures.
- Evaluating images to determine the technical quality and calibration of instrumentation.
- Evaluating new protocols.

The IAEA states, "The most widely used radioisotope in diagnostic nuclear medicine is technetium-99m. It can be attached to several specific molecules, allowing the diagnosis of many diseases, including certain types of cancers. For instance, technetium-99m-MDP (methylene diphosphonate) is widely used to detect bone metastasis associated with cancer." Nuclear medicine is a growing and important career field. Nuclear medicine technologists must have a specialized technical associate's degree or a bachelor's degree in radiology.

Sources: American Cancer Society. Retrieved April 12, 2020 from: https://www.cancer.org/treatment/treatments-and-side-effects/treatment-types/radiation/systemic-radiation-therapy.html; Diagnostic Radiopharmaceuticals. Retrieved April 12, 2020 from: https://www.iaea.org/topics/diagnostic-radiopharmaceuticals; Nuclear Medicine Technologist. Retrieved April 5, 2020 from: https://explorehealthcareers.org/career/allied-health-professions/nuclear-medicine-technologist/#academic

Concept Summary

10.1 Radioactive Nuclei

Learning Objective: Can you describe and characterize the common forms of radiation emitted during radioactive decay and other nuclear processes?

- Some nuclei are unstable and undergo radioactive decay.
- The common types of radiation emitted during decay processes are alpha, beta, and gamma.
- These types can be characterized by mass and charge values.

10.2 Equations for Nuclear Reactions

Learning Objective: Can you write balanced equations for nuclear reactions?

- Nuclear reactions can be represented by balanced equations in which the focus is on mass number and atomic number balance on each side.
- In order to make it convenient to balance mass and atomic numbers, symbols are used in nuclear equations.

10.3 Isotope Half-Life

Learning Objective: Can you solve problems using the half-life concept?

- Different radioisotopes generally decay at different rates, which are indicated by half-lives.
- One half-life is the time required for one-half of the unstable nuclei in a sample to undergo radioactive decay.

10.4 The Health Effects of Radiation

Learning Objective: Can you describe the effects of radiation on health?

- Radiation generates free radicals in tissue as it passes through.
- Radiation is hazardous even at low intensity if there is long-term exposure.
- Radiation sickness is caused by short-term intense radiation.
- Those working around radioactive sources can minimize exposure by using shielding or distance as a protection.

10.5 Measurement Units for Radiation

Learning Objective: Can you describe and compare the units used to measure quantities of radiation?

- Two systems, physical and biological, are used to describe quantities of radiation.
- Physical units indicate the number of nuclei of radioactive material that decay per unit of time.
- Biological units are related to the damage caused by radiation in living tissue.
- The common physical units are the curie and its fractions and the becquerel.
- Biological units include the roentgen (for gamma and X-rays), the rad, the gray, and the rem.

10.6 Medical Uses of Radioisotopes

Learning Objective: Can you describe, with examples, medical uses of radioisotopes?

- Radioisotopes behave chemically like nonradioisotopes of the same element and can be used diagnostically and therapeutically.
- Diagnostically, radioisotopes are used as tracers whose movement or location in the body can be followed.
- Therapeutic radioisotopes localize in diseased areas of the body, where their radiation can destroy diseased tissue.

10.7 Nonmedical Uses of Radioisotopes

Learning Objective: Can you describe, with examples, nonmedical uses of radioisotopes?

- Nonmedical uses of radioisotopes include:
  - tracers in chemical reactions
  - boundary markers between liquids in pipelines
  - tracers to detect leaks
  - metal-wear indicators
  - thickness indicators for foils and sheet metal.
- An especially interesting application is the determination of the ages of artifacts and rocks.

10.8 Induced Nuclear Reactions

Learning Objective: Can you show that you understand the concept of induced nuclear reactions?

- The bombardment of nuclei with small high-energy particles causes the bombarded nuclei to do any of the following:
  - change into stable nuclei
  - change into radioactive nuclei
  - break into smaller pieces (fission)
  - form larger nuclei (fusion).
- Most bombarding particles are accelerated by using cyclic or linear accelerators.
- Bombardment reactions have been used to produce elements that are not found in nature.

10.9 Nuclear Energy

Learning Objective: Can you describe the differences between nuclear fission and nuclear fusion reactions?

- During spontaneous nuclear fission reactions, heavy nuclei split when bombarded by neutrons and release large amounts of energy.
- This process was used to produce two atomic bombs whose use ended World War II.
- A second energy-releasing nuclear process, fusion, is the basis for today's hydrogen bombs.
- Nuclear fission is in limited use as a source of electrical power.
- This use is controversial.
- Nuclear fusion has not yet proved feasible as a controlled source of power, but research toward this end continues.

Key Terms and Concepts

Acute radiation syndrome (10.4)
Alpha particle (10.1)
Becquerel (10.5)
Beta particle (10.1)
Biological unit of radiation (10.5)
Breeder reaction (10.9)
Chain reaction (10.9)
Cold spot (10.6)
Critical mass (10.9)
Critical reaction (10.9)
Curie (10.5)
Cyclotron (10.8)
Daughter nuclei (10.2)
Electron capture (10.2)
Expanding or branching chain reaction (10.9)
Gamma ray (10.1)
Geiger–Müller tube (10.5)
Gray (10.5)
Half-life (10.3)
Hot spot (10.6)
Inverse square law of radiation (10.4)
Linear accelerator (10.8)
Moderators (10.8)
Nuclear fission (10.9)
Nuclear fusion (10.9)
Physical unit of radiation (10.5)
Positron (10.2)
Rad (10.5)
Radical or free radical (10.4)
Radioactive dating (10.7)
Radioactive decay (10.1)
Radioactive nuclei (10.1)
Radioisotope (10.2)
Rem (10.5)
Roentgen (10.5)
Scintillation counter (10.5)
Supercritical mass (10.9)
Supercritical reaction (10.9)
Thermonuclear reaction (10.9)
Tracer (10.6)
Transuranium elements (10.8)

Key Equations

1. Symbol for isotopes (**Section 10.2**):	${}^{A}_{Z}X$	
2. Conversion of a neutron to a proton and electron in the nucleus, leading to beta emission (**Section 10.2**):	${}^{1}_{0}\text{n} \rightarrow {}^{1}_{1}\text{p} + {}^{0}_{-1}\beta$	Equation 10.1
3. Variation of radiation intensity with distance (**Section 10.4**):	$\frac{I_x}{I_y} = \frac{d_y^2}{d_x^2}$	Equation 10.2
4. Fission of uranium-235 (**Section 10.9**): See also Equations 10.14, 10.15, and 10.16.	${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{135}_{53}\text{I} + {}^{97}_{39}\text{Y} + 4{}^{1}_{0}\text{n}$	Equation 10.13
5. Hydrogen fusion reaction of the sun (**Section 10.9**):	$4{}^{1}_{1}\text{H} \rightarrow {}^{4}_{2}\text{He} + 2{}^{0}_{1}\beta + 2\gamma$	Equation 10.23

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Radioactive Nuclei (Section 10.1)

10.1 Define the term *radioactive*; then criticize the following statements:

- **a.** Beta rays are radioactive.
- **b.** Radon is a stable radioactive element.

10.2 Group the common nuclear radiations (**Table 10.1**) into the following categories:

- **a.** Those with a mass number of 0
- **b.** Those with a positive charge
- **c.** Those with a charge of 0

10.3 Group the common nuclear radiations (**Table 10.1**) into the following categories:

- **a.** Those with a negative charge
- **b.** Those with a mass number greater than 0
- **c.** Those that consist of particles

10.4 Characterize the following nuclear particles in terms of the fundamental particles—protons, neutrons, and electrons:

- **a.** A beta particle
- **b.** An alpha particle
- **c.** A positron

10.5 Discuss how the charge and mass of particles that comprise radiation influence the range or ability of the radiation to penetrate matter.

Equations for Nuclear Reactions (Section 10.2)

10.6 Summarize how the atomic number and mass number of daughter nuclei compare with the original nuclei after:

- **a.** An alpha particle is emitted.
- **b.** A beta particle is emitted.
- **c.** An electron is captured.
- **d.** A gamma ray is emitted.
- **e.** A positron is emitted.

10.7 Write appropriate symbols for the following particles using the ${}^{A}_{Z}X$ symbolism:

- **a.** A tin-117 nucleus
- **b.** A nucleus of the chromium (Cr) isotope containing 26 neutrons
- **c.** A nucleus of element number 20 that contains 24 neutrons

10.8 Write appropriate symbols for the following particles using the ${}^{A}_{Z}X$ symbolism:

- **a.** A nucleus of the element in period 5 and group VB(5) with a mass number of 96
- **b.** A nucleus of element number 37 with a mass number of 80
- **c.** A nucleus of the calcium (Ca) isotope that contains 18 neutrons

10.9 Complete the following equations, using appropriate notations and formulas:

- **a.** ${}^{10}_{4}\text{Be} \rightarrow ? + {}^{10}_{5}\text{B}$
- **b.** ${}^{210}_{83}\text{Bi} \rightarrow {}^{4}_{2}\alpha + ?$
- **c.** ${}^{15}_{8}\text{O} \rightarrow ? + {}^{15}_{7}\text{N}$
- **d.** ${}^{44}_{22}\text{Ti} + {}^{0}_{-1}\text{e} \rightarrow ?$
- **e.** ${}^{8}_{4}\text{Be} \rightarrow ? + {}^{4}_{2}\text{He}$
- **f.** ${}^{46}_{23}\text{V} \rightarrow ? + {}^{46}_{22}\text{Ti}$

10.10 Complete the following equations, using appropriate notations and formulas:

- **a.** ${}^{204}_{82}\text{Pb} \rightarrow ? + {}^{4}_{2}\alpha$
- **b.** ${}^{84}_{35}\text{Br} \rightarrow ? + {}^{0}_{-1}\beta$
- **c.** $? + {}^{0}_{-1}\text{e} \rightarrow {}^{41}_{19}\text{K}$
- **d.** ${}^{149}_{62}\text{Sm} \rightarrow {}^{145}_{60}\text{Nd} + ?$
- **e.** $? \rightarrow {}^{34}_{15}\text{P} + {}^{0}_{-1}\beta$
- **f.** ${}^{15}_{8}\text{O} \rightarrow {}^{0}_{1}\beta + ?$

10.11 Write balanced equations to represent decay reactions of the following isotopes. The decay process or daughter isotope is given in parentheses.

- **a.** $^{121}_{50}\text{Sn}$ (beta emission)
- **b.** $^{55}_{26}\text{Fe}$ (electron capture)
- **c.** $^{22}_{11}\text{Na}$ (daughter = neon-22)
- **d.** $^{190}_{78}\text{Pt}$ (alpha emission)
- **e.** $^{67}_{28}\text{Ni}$ (beta emission)
- **f.** $^{67}_{31}\text{Ga}$ (daughter = Zinc-67)

10.12 Write balanced equations to represent decay reactions of the following isotopes. The decay process or daughter isotope is given in parentheses.

- **a.** $^{157}_{63}\text{Eu}$ (beta emission)
- **b.** $^{190}_{78}\text{Pt}$ (daughter = osmium-186)
- **c.** $^{138}_{62}\text{Sm}$ (electron capture)
- **d.** $^{188}_{80}\text{Hg}$ (daughter = Au-188)
- **e.** $^{234}_{90}\text{Th}$ (beta emission)
- **f.** $^{218}_{85}\text{At}$ (alpha emission)

Isotope Half-Life (Section 10.3)

10.13 What is meant by a half-life?

10.14 Describe half-life in terms of something familiar, such as a cake or cookies or your checking account.

10.15 The radioisotope rubidium-84 has been used to measure cardiac output. If Rb-84 has a half life of 33 days, how many milligrams of a 12.0 mg sample remains after 99 days?

10.16 Technetium-99 has a half-life of 6 hours. This isotope is used diagnostically to perform brain scans. A patient is given a 9.0 ng dose. How many nanograms will be present in the patient 24 hours later?

10.17 An archaeologist sometime in the future analyzes the iron used in an old building. The iron contains tiny amounts of nickel-63, with a half-life of 92 years. On the basis of the amount of nickel-63 and its decay products found, it is estimated that about 0.78% (1/128) of the original nickel-63 remains. If the building was constructed in 1980, in what year did the archaeologist make the discovery?

10.18 An archaeologist unearths the remains of a wooden box, analyzes for the carbon-14 content, and finds that about 93.75% of the carbon-14 initially present has decayed. Estimate the age of the box. The half-life of carbon-14 is 5600 years.

10.19 Germanium-66 decays by positron emission, with a half-life of 2.5 hours. What mass of germanium-66 remains in a sample after 10.0 hours if the sample originally weighed 50.0 mg?

10.20 A grain sample was found in a cave. The ratio of $^{14}_{6}\text{C}/^{12}_{6}\text{C}$ was 1/8 the value in a fresh grain sample. How old was the grain in the cave? The half-life of C-14 is 5600 years.

The Health Effects of Radiation (Section 10.4)

10.21 A source of radiation has an intensity of 130 units at a distance of 10.0 feet. How far away from the source would you have to be to reduce the intensity to 15 units?

10.22 Compare and contrast the general health effects of long-term exposure to low-level radiation and short-term exposure to intense radiation.

10.23 The element strontium is located just below calcium in the periodic table. The toxicity of radioactive strontium is due to its ability to chemically replace calcium in the human body. Write the nuclear equation for the beta emission of Sr-90.

Measurement Units for Radiation (Section 10.5)

10.24 Explain the difference between physical and biological units of radiation and give an example of each type.

10.25 Explain why the rem is the best unit to use when evaluating the radiation received by a person working in an area where exposure to several types of radiation is possible.

10.26 An individual receives a short-term whole-body dose of 3.1 rads of beta radiation. How many roentgens of X-rays would represent the same health hazard?

10.27 Describe how scintillation counters and Geiger–Müller counters detect radiation.

10.28 One Ci corresponds to 3.7×10^{10} nuclear disintegrations per second. How many disintegrations per second would take place in a sample containing 4.6 μ Ci of radioisotope?

Medical Uses of Radioisotopes (Section 10.6)

10.29 Explain what a diagnostic tracer is and list the ideal characteristics one should have.

10.30 Describe the importance of hot and cold spots in diagnostic work using tracers.

10.31 List the ideal characteristics of a radioisotope that is to be administered internally for therapeutic use.

10.32 Chromium-51 is used medically to monitor kidney activity. Chromium-51 decays by electron capture. Write a balanced equation for the decay process and identify the daughter that is produced.

10.33 Gold-198 is a β emitter used to treat leukemia. It has a half-life of 2.7 days. The dosage is 1.0 mCi/kg body weight. How long would it take for a 70.0 mCi dose to decay to an activity of 2.2 mCi?

Nonmedical Uses of Radioisotopes (Section 10.7)

10.34 A mixture of water (H_2O) and hydrogen peroxide (H_2O_2) will give off oxygen gas when solid manganese dioxide is added as a catalyst. Describe how you could use a tracer to determine if the oxygen comes from the water or the peroxide.

10.35 Suppose you are planning a TV commercial for motor oil. Describe how you would set it up to show that your oil prevents engine wear better than a competing brand.

10.36 Propose a method for measuring the volume of water in an irregularly shaped swimming pool. You have 1 gallon of water that contains a radioisotope with a long half-life, and a Geiger–Müller counter.

10.37 Explain why carbon-14, with a half-life of about 5600 years, is not a good radioisotope to use if you want to determine the age of a coal bed thought to be several million years old.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Induced Nuclear Reactions (Section 10.8)

10.38 Write a balanced equation to represent the synthesis of silicon-27 that takes place when magnesium-24 reacts with an accelerated alpha particle. A neutron is also produced.

10.39 Complete the following reactions by identifying the missing nuclear symbols.

a. ${}^{9}_{4}\text{Be} + ? \rightarrow {}^{12}_{6}\text{C} + {}^{1}_{0}\text{n}$

b. ${}^{27}_{13}\text{Al} + ? \rightarrow {}^{30}_{15}\text{P} + {}^{1}_{0}\text{n}$

c. ${}^{27}_{13}\text{Al} + {}^{2}_{1}\text{H} \rightarrow ? + {}^{4}_{2}\alpha$

d. ${}^{14}_{7}\text{N} + {}^{4}_{2}\alpha \rightarrow ? + {}^{1}_{1}\text{H}$

10.40 Write a balanced equation to represent the net breeding reaction that occurs when uranium-238 reacts with a neutron to form plutonium-239 and two beta particles.

10.41 Explain why neutrons cannot be accelerated in a cyclotron or linear accelerator.

10.42 Describe the role of a moderator in nuclear reactions involving neutrons.

10.43* To make indium-111 for diagnostic work, silver-109 is bombarded with α particles. What isotope forms when a silver-109 nucleus captures an α particle? Write an equation to represent the process. What two particles must be emitted by the isotope to form indium-111?

10.44 To make gallium-67 for diagnostic work, zinc-66 is bombarded with accelerated protons. Write a balanced equation to represent the process when a zinc-66 nucleus captures a single proton.

Nuclear Energy (Section 10.9)

10.45 Write one balanced equation that illustrates nuclear fission.

10.46 Write one balanced equation that illustrates nuclear fusion.

10.47 Explain why critical mass is an important concept in neutron-induced fission chain reactions.

10.48 Describe the difference between nuclear fission and nuclear fusion processes. Use nuclear equations to illustrate the difference.

10.49 Complete the following equations, which represent two additional ways uranium-235 can undergo nuclear fission.

a. ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{160}_{62}\text{Sm} + ? + 4{}^{1}_{0}\text{n}$

b. ${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{87}_{35}\text{Br} + ? + 3{}^{1}_{0}\text{n}$

10.50 Plutonium-238 is used to power batteries for pacemakers. It decays by α emission. Write a balanced equation for the process.

Additional Exercises

10.51 Polonium-210 decays by alpha emission and has a half-life of 138 days. Suppose a sample of Po-210 contains 6.02×10^{20} Po-210 atoms and undergoes decay for 138 days. What was the mass in grams of the original sample? Assume all alpha particles formed by the decay escape, and the daughter nuclei remain in the sample as nonradioactive isotopes; then calculate the mass of the sample in grams after 138 days.

10.52 Propose an explanation for the fact that the fusion reactions occurring in the sun only take place at extremely high temperatures.

10.53 Explain how you would make a 10.0 mL sample of 0.100 M NaI that contained iodine in the form of the ${}^{123}_{53}\text{I}$ isotope.

10.54 Zinc-71 decays by beta emission, and has a half-life of 2.4 minutes. Suppose a 0.200 g sample of Zn-71 was put inside the tube of a Geiger–Müller counter that counted every beta particle emitted by the sample for 2.4 minutes. What would the average reading of the Geiger–Müller counter be in counts per minute during the 2.4 minutes? How many curies is this?

10.55 At one time, nuclear bombs were tested by exploding them aboveground. The fallout from such tests contained some Sr-90, a radioactive isotope of strontium. If Sr-90 gets into the food supply, it can become incorporated into the bones of humans and other animals. Explain how this can happen even though strontium is not a normal component of bones.

Chemistry for Thought

10.56 One (unrealized) goal of ancient alchemists was to change one element into another (such as lead to gold). Do such changes occur naturally? Explain your reasoning.

10.57 Nuclear accidents, such as the one at Chernobyl, can release radioactive iodine and other radioisotopes into the atmosphere. Why might the distribution of potassium iodide (nonradioactive) tablets to the population be effective in countering radiation sickness?

10.58 Consider the concept of half-life and decide if, in principle, a radioactive isotope ever completely disappears by radioactive decay. Explain your reasoning.

10.59 Diagnostic procedures rely on radioisotopes that are gamma, beta, or positron emitters. Why are alpha emitters not useful for diagnostic purposes?

10.60 Nuclear wastes typically have to be stored for at least 20 half-lives before they are considered safe. This can be a time of hundreds or thousands of years for some isotopes. With that in mind, would you consider sending such wastes into outer space a responsible solution to the nuclear waste disposal problem? Explain your answer.

10.61 Read Health Connections 10.2 and write an equation to represent the radioactive decay of radon-222. Then, write an equation to represent the decay of the daughter produced by the radon decay. The daughter decays by alpha emission. Then, write an equation for the decay of the daughter produced by this second reaction, which decays by beta emission. In each of the three reactions, assume that only one particle in addition to the daughter is produced. What element is radon converted into by this series of three decays?

10.62 Uranium-238 is the most abundant naturally occurring isotope of uranium. It undergoes radioactive decay to form other isotopes. In the first three steps of this decay, uranium-238 is converted to thorium-234, which is converted to protactinium-234, which is then converted to uranium-234. Assume that only one particle in addition to the daughter is produced in each step, and use equations for the decay processes to determine the type of radiation emitted during each step.

11 Organic Compounds: Alkanes

djile/Shutterstock.com

Environmental Career Focus

APIARIST (BEEKEEPER)

"Beekeeping as a hobby is one thing, but doing this as a business is something else entirely," I explain from behind the counter of my boutique gift shop featuring beeswax candles, nutritional supplements, bee-themed jewelry, and of course—local honey.

I became keenly interested in honeybees while working on a botany degree. My research project about the role of honeybees in sustaining native plant species garnered several scholarships. I was able to create my own "Bachelor of Integrated Studies" degree in botany, zoology, and entrepreneurship.

"I'm fascinated by bees—how they make these products with their own bodies: honey, wax, royal jelly, and the antibacterial propolis I use in my self-care products. What I learned in school about business, chemistry, laboratory skills, plants, and bee parasites all plays a part in my success today. Running a small business is hard work—but when you do what you love and help the environment at the same time—it's all worth it."

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Show that you understand the general importance of organic chemical compounds. **(Section 11.1**)
2. Be able to recognize the molecular formulas of organic and inorganic compounds. **(Section 11.1)**
3. Explain some general differences between inorganic and organic compounds. **(Section 11.2)**
4. Be able to use structural formulas to identify compounds that are isomers of each other. **(Section 11.3)**
5. Write condensed or expanded structural formulas for compounds. **(Section 11.4)**
6. Classify alkanes as normal or branched. **(Section 11.5)**
7. Use structural formulas to determine whether compounds are structural isomers. **(Section 11.6)**
8. Assign IUPAC names and draw structural formulas for alkanes. **(Section 11.7)**

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

9 Assign IUPAC names and draw structural formulas for cycloalkanes. **(Section 11.8)**

10 Name and draw structural formulas for *cis-trans* isomers of cycloalkanes. **(Section 11.9)**

11 Describe the key physical properties of alkanes. **(Section 11.10)**

12 Write alkane combustion reactions. **(Section 11.11)**

THE WORD *ORGANIC* IS used in several different contexts. Scientists of the 18th and 19th centuries studied compounds extracted from plants and animals and labeled them "organic" because they had been obtained from organized (living) systems. Organic fertilizer is organic in the original sense that it comes from a living organism. There is no universal definition of organic foods (see **Figure 11.1**), but the term is generally taken to mean foods grown without the application of pesticides or synthetic fertilizers. When referring to organic chemistry, however, we mean the chemistry of carbon-containing compounds.

Rawpixel.com/Shutterstock.com

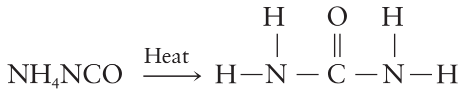
FIGURE 11.1 Grocery stores usually have a separate produce area for fruits and vegetables labeled organic.

11.1 Carbon: The Element of Organic Compounds

Learning Objectives 1 Show that you understand the general importance of organic chemical compounds.

Learning Objectives 2 Be able to recognize the molecular formulas of organic and inorganic compounds.

Early chemists thought organic compounds could be produced only through the action of a "vital force," a special force active only in living organisms. This idea was central to the study of organic chemistry until 1828, because up to that time, no one had been able to synthesize an organic compound from its elements or from naturally occurring minerals. In that year, Friedrich Wöhler, a German chemist, heated an inorganic salt called ammonium cyanate and produced urea. This compound, normally found in blood and urine, was unquestionably organic, and it had come from an inorganic source. The reaction is



$$\underset{\text{ammonium cyanate}}{NH_4NCO} \xrightarrow{\text{Heat}} \underset{\text{urea}}{H-\overset{\displaystyle H\atop|}{N}-\overset{\displaystyle O\atop\|}{C}-\overset{\displaystyle H\atop|}{N}-H} \qquad (11.1)$$

Wöhler's urea synthesis discredited the "vital force" theory, and his success prompted other chemists to attempt to synthesize organic compounds. Today, organic compounds are being synthesized in thousands of laboratories, and most of the synthetics have never been isolated from natural sources.

Organic compounds share one unique feature: They all contain carbon. Therefore, **organic chemistry** is defined as the study of carbon-containing compounds. There are a few exceptions to this definition; a small number of carbon compounds—such as CO, CO_2, carbonates, and cyanides—were studied before Wöhler's urea synthesis. These were classified as inorganic because they were obtained from nonliving

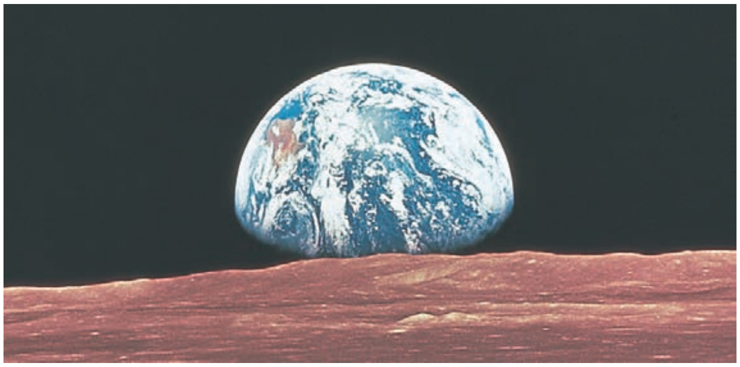
organic compound A compound that contains the element carbon.

organic chemistry The study of carbon-containing compounds.

inorganic chemistry The study of the elements and all noncarbon compounds.

systems, and even though they contain carbon, we still consider them to be a part of **inorganic chemistry**.

The importance of carbon compounds to life on Earth cannot be overemphasized. If all carbon compounds were removed from the Earth, its surface would be somewhat like the barren surface of the moon (see **Figure 11.2**). There would be no animals, plants, or any other form of life. If carbon-containing compounds were removed from the human body, all that would remain would be water, a very brittle skeleton, and a small residue of minerals. Many of the essential constituents of living matter—such as carbohydrates, fats, proteins, nucleic acids, enzymes, and hormones—are organic chemicals.



NASA

FIGURE 11.2 Organic chemistry makes a tremendous difference when comparing the physical makeup of the Earth and the moon.

The essential needs of daily human life are food, fuel, shelter, and clothing. The principal components of food (with the exception of water) are organic. The fuels we use (e.g., wood, coal, petroleum, and natural gas) are mixtures of organic compounds. Our homes typically incorporate wood construction, and our clothing, whether made of natural or synthetic fibers, is organic.

Besides the major essentials, many of the smaller everyday things often taken for granted are also derived from carbon and its compounds. Consider an ordinary pencil. The "lead" (actually graphite), the wood, the rubber eraser, and the paint on the surface are all either carbon or carbon compounds. The paper in this book, the ink on its pages, and the glue holding it all together are also made of carbon compounds.

11.2 Organic and Inorganic Compounds Compared

Learning Objective 3 Explain some general differences between inorganic and organic compounds.

It is interesting that the subdivision of chemistry into its organic and inorganic branches results in one branch that deals with compounds composed mainly of one element and another branch that deals with compounds formed by the more than 100 remaining elements. However, this classification seems more reasonable when we recognize that known organic compounds are much more numerous than inorganic compounds. An estimated 500,000 inorganic compounds have been identified, but more than 9 million organic compounds are known, and thousands of new ones are synthesized or isolated each year.

One of the reasons for the large number of organic compounds is the unique ability of carbon atoms to form stable covalent bonds with other carbon atoms and with atoms of other elements. The resulting covalently bonded molecules may contain as few as one or more than a million carbon atoms.

In contrast, inorganic compounds are often characterized by the presence of ionic bonding. Covalent bonding also may be present, but it is less common. These differences

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

generally cause organic and inorganic compounds to differ physically (see **Figure 11.3**) and chemically, as shown in **Table 11.1**.

Adam Crowley/Getty Images

FIGURE 11.3 Many organic compounds, such as ski wax, have relatively low melting points. What does this fact reveal about the forces between organic molecules?

TABLE 11.1 Properties of Typical Organic and Inorganic Compounds

Property	Organic Compounds	Inorganic Compounds
Bonding within molecules	Covalent	Often ionic
Forces between molecules	Generally weak	Quite strong
Normal physical state	Gases, liquids, or low-melting-point solids	Usually high-melting-point solids
Flammability	Often flammable	Usually nonflammable
Solubility in water	Often low	Often high
Conductivity of water solutions	Nonconductor	Conductor
Rate of chemical reactions	Usually slow	Usually fast

✔ **LEARNING CHECK 11.1** Classify each of the following compounds as organic or inorganic:

a. NaCl d. NaOH
b. CH_4 e. CH_3OH
c. C_6H_6 f. $Mg(NO_3)_2$

✔ **LEARNING CHECK 11.2** Decide whether each of the following characteristics most likely describes an organic or inorganic compound:

a. Flammable b. Low boiling point c. Soluble in water

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STUDY TOOLS 11.1

Changing Gears for Organic Chemistry

You will find that organic chemistry is very different from general or inorganic chemistry. By quickly picking up on the changes, you will help yourself prepare for quizzes and exams.

There is almost no math in these next five chapters or in the biochemistry section. Very few mathematical formulas need to be memorized. The problems you will encounter fall mainly into four categories: naming compounds and drawing structures, describing physical properties of substances, writing reactions, and identifying typical uses of compounds. This pattern holds true for all six of the organic chemistry chapters.

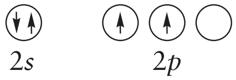
The naming of compounds is introduced in this chapter, and the rules developed here will serve as a starting point in the next five chapters. Therefore, it is important to master naming in this chapter. A well-developed skill in naming will help you do well on exams covering the coming chapters.

Only a few reactions are introduced in this chapter, but many more will be in future chapters. Writing organic reactions is just as important (and challenging) as naming structures, and Study Tools 12.1 will help you to learn this skill. Identifying the uses of compounds can best be handled by making a list as you read the chapter or by highlighting compounds and their uses so that they are easy to review. All four categories of problems are covered by numerous end-of-chapter exercises to give you practice.

11.3 Bonding Characteristics and Isomerism

Learning Objective 4 Be able to use structural formulas to identify compounds that are isomers of each other.

There are two major reasons for the astonishing number of organic compounds: the bonding characteristics of carbon atoms, and the isomerism of carbon-containing molecules. As a group IVA(14) element, a carbon atom has four valence electrons. Two of these outermost-shell electrons are in an *s* orbital, and two are in *p* orbitals (see **Section 3.4**):



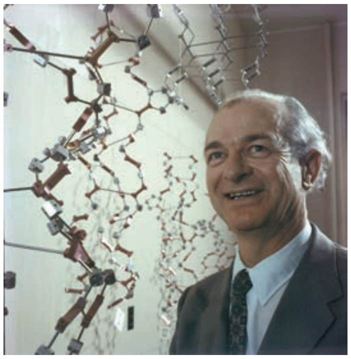

J. R. Eyerman/The LIFE Picture Collection/Getty Images

FIGURE 11.4 Linus Pauling was an American chemist, chemical engineer, peace activist, author, and educator.

With only two unpaired electrons, we might predict that carbon would form just two covalent bonds with other atoms. Yet, we know from the formula of methane (CH_4) that carbon forms four bonds.

Linus Pauling (1901–1994; see **Figure 11.4**), winner of the Nobel Prize in chemistry (1954) and Nobel Peace Prize (1963), developed a useful model to explain the bonding characteristics of carbon. Pauling found that a mathematical mixing of the 2*s* and three 2*p* orbitals could produce four new, equivalent orbitals (see **Figure 11.5**). Each of these **hybrid orbitals** has the same energy and is designated as sp^3. An sp^3 orbital has a two-lobed shape, similar to the shape of a *p* orbital but with different-sized lobes (see **Figure 11.6**). Each of the four sp^3 hybrid orbitals contains a single unpaired electron available for covalent bond formation. Thus, carbon forms four bonds.

hybrid orbital An orbital produced from the combination of two or more nonequivalent orbitals of an atom.

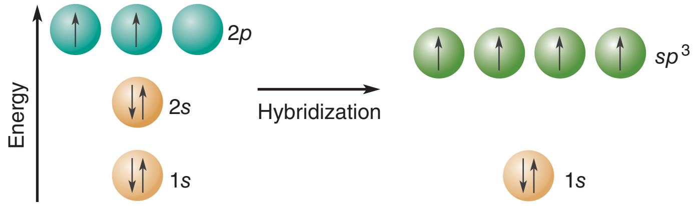


FIGURE 11.5 The mixing of 2*s* and three 2*p* orbitals of a carbon atom to generate four sp^3 carbon orbitals, each with energy intermediate between 2*s* and 2*p* orbitals.

Each carbon–hydrogen bond in methane arises from an overlap of a C (sp^3) and an H ($1s$) orbital. The sharing of two electrons in this overlap region creates a sigma (σ) bond. The four equivalent sp^3 orbitals point toward the corners of a regular tetrahedron (see **Figure 11.7**).

Carbon atoms also have the ability to bond covalently to other carbon atoms to form chains and networks. This means that two carbon atoms can join by sharing two electrons to form a single covalent bond:

$$\cdot\underset{\cdot}{\dot{C}}\cdot + \cdot\underset{\cdot}{\dot{C}}\cdot \longrightarrow \cdot\underset{\cdot}{\dot{C}}{:}\underset{\cdot}{\dot{C}}\cdot \qquad \text{or} \qquad \cdot\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}\cdot \tag{11.2}$$

A third carbon atom can join the end of this chain:

$$\cdot\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}\cdot + \cdot\underset{\cdot}{\dot{C}}\cdot \longrightarrow \cdot\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}\cdot \tag{11.3}$$

This process can continue and form carbon chains of almost any length, such as

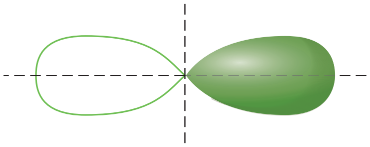
$$\cdot\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}-\underset{\cdot}{\dot{C}}\cdot$$

The electrons not involved in forming the chain can be shared with electrons of other carbon atoms (to form chain branches) or with electrons of other elements such as hydrogen, oxygen, or nitrogen. Carbon atoms may also share more than one pair of electrons to form multiple bonds:

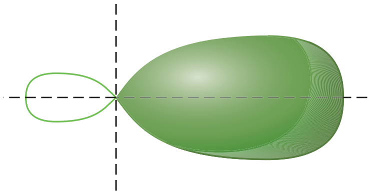
$$\cdot\underset{\cdot}{\dot{C}}-\dot{C}=\dot{C}-\underset{\cdot}{\dot{C}}\cdot \qquad\qquad \cdot\underset{\cdot}{\dot{C}}-C\equiv C-\underset{\cdot}{\dot{C}}\cdot$$

Chain with double bond

Chain with triple bond



A $2p$ orbital



An sp^3 hybrid orbital

FIGURE 11.6 A comparison of unhybridized p and sp^3 hybridized orbital shapes. The atomic nucleus is at the junction of the lobes in each case.

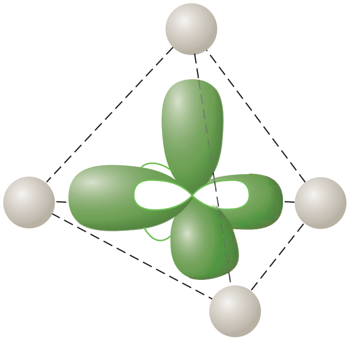


FIGURE 11.7 Directional characteristics of sp^3 hybrid orbitals of carbon and the formation of C—H bonds in methane (CH_4). The hybrid orbitals point toward the corners of a regular tetrahedron. Hydrogen $1s$ orbitals are illustrated in position to form bonds by overlap with the major lobes of the hybrid orbitals.

In principle, there is no limit to the number of carbon atoms that can bond covalently. Thus, organic molecules range from the simple molecules such as methane (CH_4) to very complicated molecules containing over a million carbon atoms.

The variety of possible carbon atom arrangements is even more important than the size range of the resulting molecules. The carbon atoms in all but the very simplest organic molecules can bond in more than one arrangement, giving rise to different compounds with different structures and properties. This property, called **isomerism**, is characterized by compounds that have identical molecular formulas but different arrangements of atoms. One type of isomerism is characterized by compounds called **structural isomers**. Another type of isomerism is introduced in **Section 11.9**.

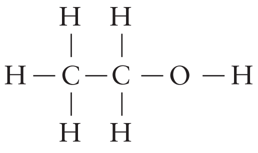
The existence of covalent bonding explains why there are literally millions of potential medicines undiscovered in nature. Currently, about 40% of drugs come from plant sources.

Example 11.1 Using Rules for Covalent Bonding

Use the usual rules for covalent bonding to show that a compound with the molecular formula C_2H_6O demonstrates the property of isomerism. Draw formulas for the isomers, showing all covalent bonds.

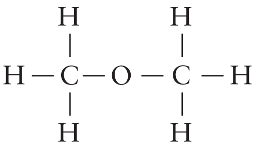
Solution

Carbon forms four covalent bonds by sharing its four valence-shell electrons. Similarly, oxygen should form two covalent bonds, and hydrogen a single bond. On the basis of these bonding relationships, two structural isomers are possible:



$$H-\underset{H}{\overset{H}{\mid}}\!\!\!\!C-\underset{H}{\overset{H}{\mid}}\!\!\!\!C-O-H$$

ethyl alcohol



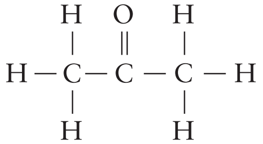
$$H-\underset{H}{\overset{H}{\mid}}\!\!\!\!C-O-\underset{H}{\overset{H}{\mid}}\!\!\!\!C-H$$

dimethyl ether

isomerism A property in which two or more compounds have the same molecular formula but different arrangements of atoms.

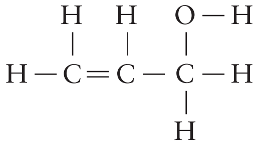
structural isomers Compounds that have the same molecular formula but in which the atoms bond in different patterns.

✔ **LEARNING CHECK 11.3** Which one of the structures below represents a structural isomer of

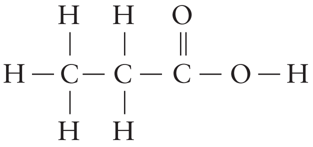


$$\begin{array}{ccccccccc} & & H & & O & & H & & \\ & & | & & \| & & | & & \\ H & - & C & - & C & - & C & - & H \\ & & | & & & & | & & \\ & & H & & & & H & & \end{array}$$

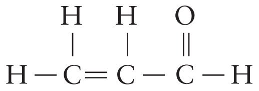
?

a. 

$$\begin{array}{ccccccccc} & & H & & H & & O & - & H \\ & & | & & | & & | & & \\ H & - & C & = & C & - & C & - & H \\ & & & & & & | & & \\ & & & & & & H & & \end{array}$$

c. 

$$\begin{array}{ccccccccccc} & & H & & H & & O & & & & \\ & & | & & | & & \| & & & & \\ H & - & C & - & C & - & C & - & O & - & H \\ & & | & & | & & & & & & \\ & & H & & H & & & & & & \end{array}$$

b. 

$$\begin{array}{ccccccccc} & & H & & H & & O & & \\ & & | & & | & & \| & & \\ H & - & C & = & C & - & C & - & H \end{array}$$

smereka/Shutterstock.com

FIGURE 11.8 A number of grains can be fermented and distilled to produce alcohol, including wheat, corn, rice, and rye. Grain alcohol is considered a "neutral spirit," meaning it has no added flavor.

The two isomers of Example 11.1 are quite different. Ethyl alcohol (grain alcohol; see **Figure 11.8**) is a liquid at room temperature, whereas dimethyl ether is a gas. As we've seen before, the structural differences exert a significant influence on properties. From this example, we can see that molecular formulas such as C_2H_6O provide much less information about a compound than do structural formulas. **Figure 11.9** shows ball-and-stick models of these two molecules.

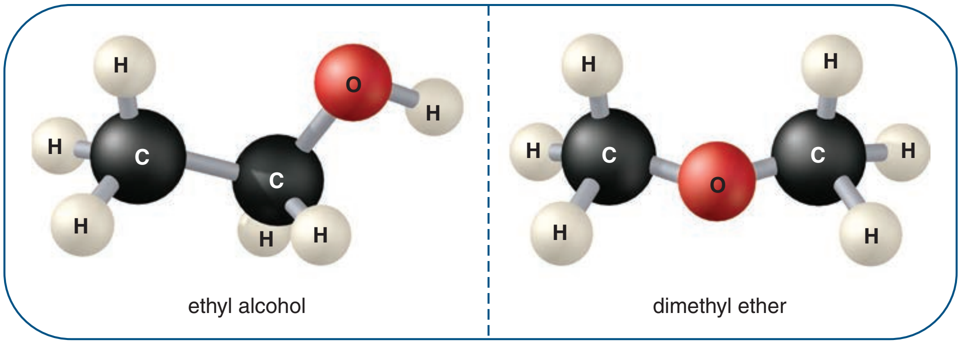


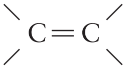
FIGURE 11.9 Ball-and-stick models of the isomers of C_2H_6O. Ethyl alcohol is a liquid at room temperature and completely soluble in water, whereas dimethyl ether is a gas at room temperature and only partially soluble in water.

As the number of carbon atoms in the molecular formula increases, the number of possible isomers increases dramatically. For example, 366,319 different isomers are possible for a molecular formula of $C_{20}H_{42}$. No one has prepared all these isomers or even drawn their structural formulas, but the number helps us to understand why so many organic compounds have been either isolated from natural sources or synthesized.

11.4 Functional Groups: The Organization of Organic Chemistry

Learning Objective 5 Write condensed or expanded structural formulas for compounds.

Because of the enormous number of possible compounds, the study of organic chemistry might appear to be hopelessly difficult. However, the arrangement of organic compounds into a relatively small number of classes can simplify the study a great deal. This organization is done on the basis of characteristic structural features called **functional groups**. For example, compounds with a carbon–carbon double bond



functional group A unique reactive combination of atoms that differentiates molecules of organic compounds of one class from those of another.

are classified as alkenes. The major classes and functional groups are given in **Table 11.2**. Notice that each functional group in **Table 11.2** (except for alkanes) contains a multiple bond or at least one oxygen or nitrogen atom. The characteristics and activities associated with living organisms (see **Figure 11.10**) are made possible by reactions involving organic molecules with functional groups.

In **Table 11.2**, we have used both expanded and condensed structural formulas for the compounds. **Expanded structural formulas** show all covalent bonds, whereas **condensed structural formulas** show only specific bonds. You should become familiar with both types, but especially with condensed formulas because they will be used often.

expanded structural formula A structural molecular formula showing all the covalent bonds.

condensed structural formula A structural molecular formula showing the general arrangement of atoms but without showing all the covalent bonds.

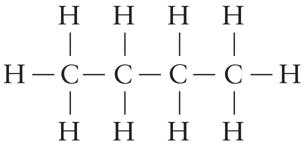
vladsilver/Shutterstock.com

FIGURE 11.10 Organic molecules with functional groups are involved in all the characteristics of and reactions within living organisms. For example, organic molecules determine the color of a penguin's feathers, the reactions that enable fat storage, and even the complex emotions involved in parenting.

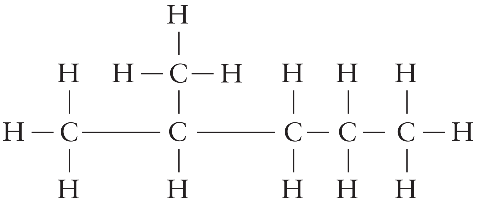
Example 11.2 Writing Condensed Structural Formulas

Recognizing and writing structural formulas is an important skill in biological areas of study because structure determines properties.

Write a condensed structural formula for each of the following compounds:

a. 

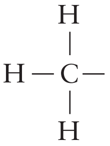
$$\begin{array}{ccccccccccc} & & H & & H & & H & & H & & \\ & & | & & | & & | & & | & & \\ H & - & C & - & C & - & C & - & C & - & H \\ & & | & & | & & | & & | & & \\ & & H & & H & & H & & H & & \end{array}$$

b. 

$$\begin{array}{ccccccccccccc} & & & & H & & & & & & & & \\ & & & & | & & & & & & & & \\ & & H & & H-C-H & & H & & H & & H & & \\ & & | & & | & & | & & | & & | & & \\ H & - & C & —— & C & —— & C & - & C & - & C & - & H \\ & & | & & | & & | & & | & & | & & \\ & & H & & H & & H & & H & & H & & \end{array}$$

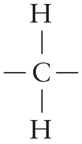
Solution

a. Usually the hydrogens belonging to a carbon are grouped to the right. Thus, the group



$$\begin{array}{ccc} & H & \\ & | & \\ H- & C & - \\ & | & \\ & H & \end{array}$$

condenses to CH_3—, and



$$\begin{array}{ccc} & H & \\ & | & \\ - & C & - \\ & | & \\ & H & \end{array}$$

condenses to —CH_2—. Thus, the formula condenses to

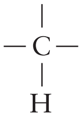
$$CH_3—CH_2—CH_2—CH_3$$

Other acceptable condensations are

$$CH_3CH_2CH_2CH_3 \qquad \text{and} \qquad CH_3(CH_2)_2CH_3$$

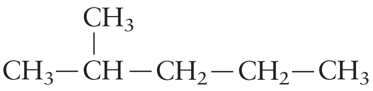
Parentheses are used here to denote a series of two —CH_2— groups.

b. The group



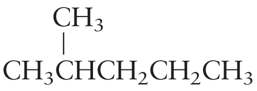
$$\begin{array}{ccc} & | & \\ - & C & - \\ & | & \\ & H & \end{array}$$

condenses to $-\overset{|}{\mathrm{CH}}-$. The condensed formula is therefore



$$\mathrm{CH_3-\overset{\displaystyle CH_3}{\overset{|}{C}}H-CH_2-CH_2-CH_3}$$

or

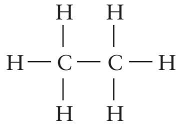
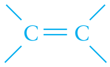
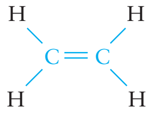
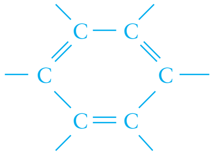
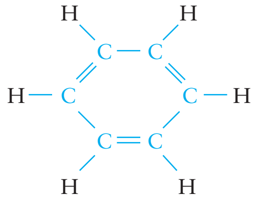
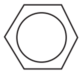
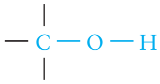
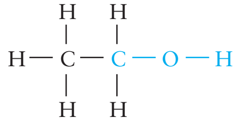
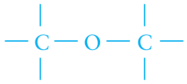
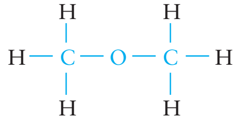
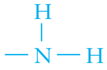
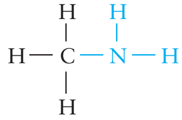
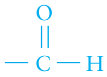
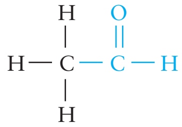
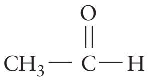
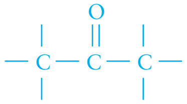
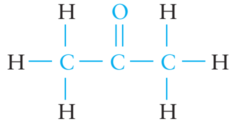
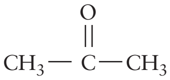
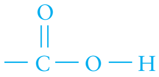
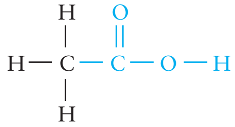
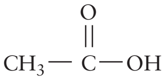
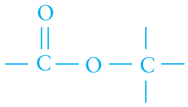
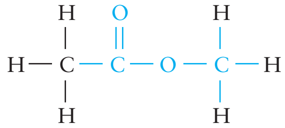
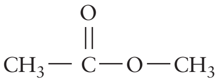
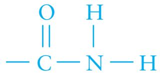
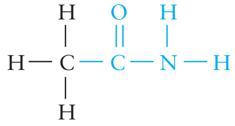
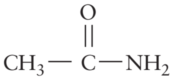


$$\mathrm{CH_3\overset{\displaystyle CH_3}{\overset{|}{C}}HCH_2CH_2CH_3}$$

or

$$(CH_3)_2CH(CH_2)_2CH_3$$

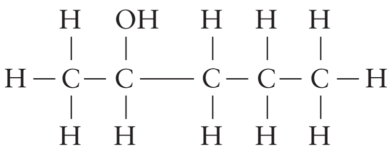
TABLE 11.2 Classes and Functional Groups of Organic Compounds

Class	Functional Group	Example of Expanded Structural Formula	Example of Condensed Structural Formula	Common Name
Alkane	None		CH_3CH_3	ethane
Alkene			$H_2C{=}CH_2$	ethylene
Alkyne	$-C{\equiv}C-$	$H-C{\equiv}C-H$	$HC{\equiv}CH$	acetylene
Aromatic				benzene
Alcohol			CH_3CH_2-OH	ethyl alcohol
Ether			CH_3-O-CH_3	dimethyl ether
Amine			CH_3-NH_2	methylamine
Aldehyde			 $CH_3-\overset{O}{\overset{\|}{C}}-H$	acetaldehyde
Ketone			 $CH_3-\overset{O}{\overset{\|}{C}}-CH_3$	acetone
Carboxylic acid			 $CH_3-\overset{O}{\overset{\|}{C}}-OH$	acetic acid
Ester			 $CH_3-\overset{O}{\overset{\|}{C}}-O-CH_3$	methyl acetate
Amide			 $CH_3-\overset{O}{\overset{\|}{C}}-NH_2$	acetamide

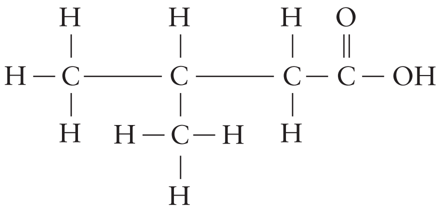
In the last form, the first set of parentheses indicates two identical CH_3 groups attached to the same carbon atom, and the second set of parentheses denotes two CH_2 groups.

✔ **LEARNING CHECK 11.4** Write a condensed structural formula for each of the following compounds. Retain the bonds to and within the functional groups.

a.



b.



11.5 Alkane Structures

Learning Objective 6 Classify alkanes as normal or branched.

Hydrocarbons, the simplest of all organic compounds, contain only two elements, carbon and hydrogen. **Saturated hydrocarbons**, or **alkanes**, are organic compounds in which carbon is bonded to four other atoms by single bonds; there are no double or triple bonds in the molecule. Unsaturated hydrocarbons, studied later, are called alkenes, alkynes, and aromatics and contain double bonds, triple bonds, or six-carbon rings, as shown in **Figure 11.11**.

hydrocarbon An organic compound that contains only carbon and hydrogen.

saturated hydrocarbon Another name for an alkane.

alkane A hydrocarbon that contains only single bonds.

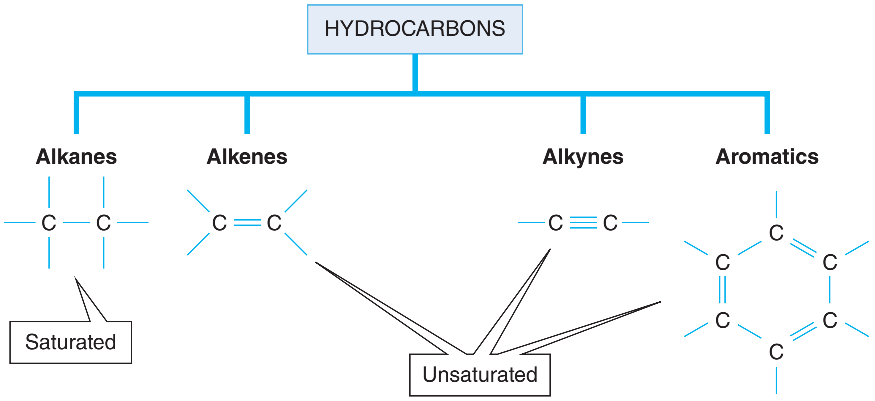


FIGURE 11.11 Classification of hydrocarbons.

Most life processes are based on the reactions of functional groups. Since alkanes have no functional group, they are not abundant in the human body. However, most compounds in human cells contain parts consisting solely of carbon and hydrogen that behave very much like hydrocarbons. Thus, to understand the chemical properties of the more complex biomolecules, it is useful to have some understanding of the structure, physical properties, and chemical behavior of hydrocarbons.

Another important reason for becoming familiar with the characteristics of hydrocarbons is the crucial role they play in modern industrial society. We use naturally occurring hydrocarbons as primary sources of energy and as important sources of raw materials for the manufacture of plastics, synthetic fibers, drugs, and hundreds of other compounds used daily (see **Figure 11.12**).

Alkanes can be represented by the general formula C_nH_{2n+2}, where n is the number of carbon atoms in the molecule. The simplest alkane, methane, contains one carbon atom and therefore has the molecular formula CH_4. The carbon atom is at the center, and the four bonds of the carbon atom are directed toward the hydrogen atoms at the corners of

Steve Gorton/Getty Images

FIGURE 11.12 This golf club has the strength and light weight of aluminum yet is made from graphite (carbon) fibers reinforced with plastic. What other sports equipment is made from graphite fibers?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS **11.1**

Is organic food worth the price?

"Organic" is a designation used by the United States Department of Agriculture to certify food that is produced without the use of antibiotics, hormones, synthetic chemicals or fertilizers, most pesticides, bioengineering, ionizing radiation, or sewage sludge. During the past decade, the use of organic foods, including produce, meat, dairy, and even packaged foods, has undergone huge growth. This growth has been tempered by the fact that they are still generally more expensive than conventionally produced food. Does the extra expense justify the higher price? Many believe that organic products are higher in nutrients, but a recent systematic review of studies performed over the past 50 years did not find a difference in nutrient quality between organic and conventionally grown produce. When it comes to pesticide and chemical exposure, the reality is that we are exposed to potentially harmful chemicals in many things, ranging from consumer products, air, drinking water, pollution, food, and even our homes. In fact, the levels of pesticides allowed in agricultural products in the United States are much more strictly regulated than what people can spray in their homes.

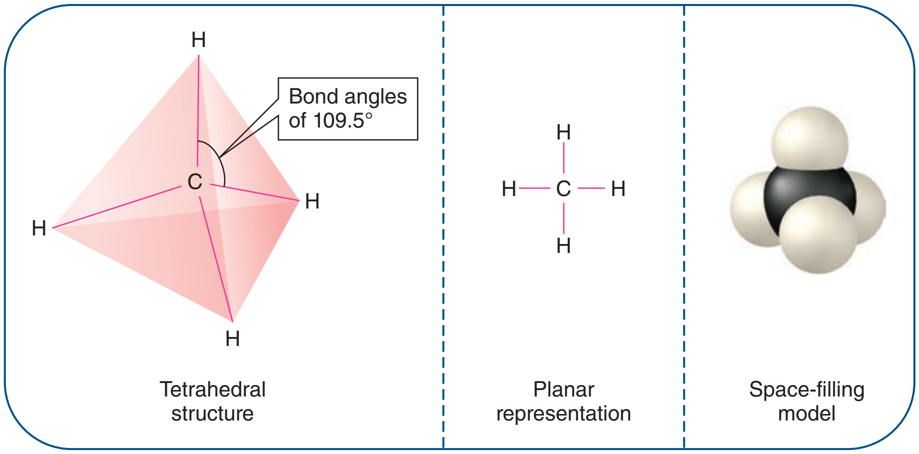
Until convincing evidence to the contrary becomes available, the benefits of eating fruits and vegetables—which are low in calories and loaded with vitamins, minerals, and disease-fighting phytonutrients—even if they are not organically grown, likely far outweigh the risk for most people. Choose organic when you can, but the most important thing you can do is make sure to get plenty of variety when it comes to produce. This will minimize your exposure and maximize your nutrition and health. The least-contaminated produce are often those protected by an outer coating (such as a corn husk) or thick skin (oranges, pineapple, watermelon, kiwi, cantaloupe, avocado, grapefruit, mango), so you can use that as a rough guide to direct you to produce with lower levels of pesticides.

Cengage Learning/Charles D. Winters

Outer coatings on produce help minimize the exposure to pesticides.

a regular tetrahedron; each hydrogen atom is geometrically equivalent to the other three in the molecule (see **Figure 11.13**). A tetrahedral orientation of bonds with bond angles of 109.5° is typical for carbon atoms that form four single bonds. Methane is the primary compound in natural gas. Tremendous quantities of natural gas are consumed worldwide because methane is an efficient, clean-burning fuel. It is used to heat homes, cook food, and power factories.

FIGURE 11.13 Structural representations of methane, CH_4.



Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The next alkane is ethane, which has the molecular formula C_2H_6 and the structural formula $CH_3—CH_3$. This molecule may be thought of as a methane molecule with one hydrogen removed and a $—CH_3$ put in its place. Again, the carbon bonds have a tetrahedral geometry as shown in **Figure 11.14**. Ethane is a minor component of natural gas.

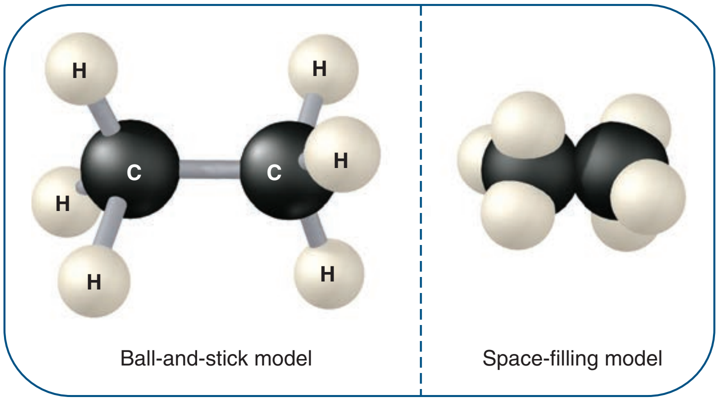
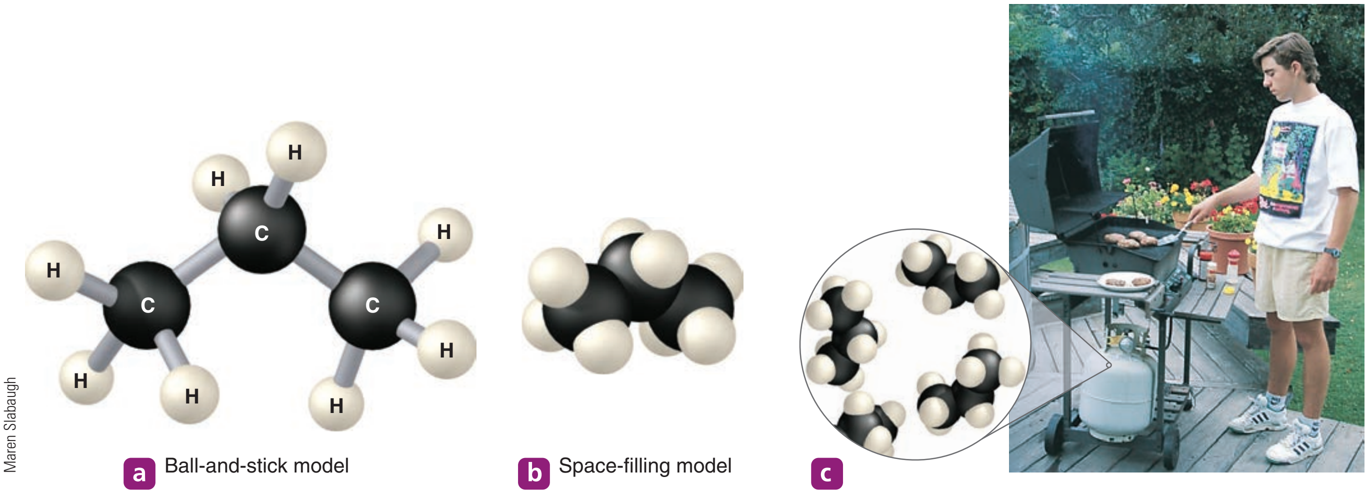


FIGURE 11.14 Perspective models of the ethane molecule, CH_3CH_3.

Propane, the third alkane, has the molecular formula of C_3H_8 and the structural formula $CH_3—CH_2—CH_3$. Again, we can produce this molecule by removing a hydrogen atom from the preceding compound (ethane) and substituting a $—CH_3$ in its place (see **Figure 11.15**). Since all six hydrogen atoms of ethane are equivalent, it makes no difference which one is replaced. Propane is used extensively as an industrial fuel, as well as for home heating and cooking (see **Figure 11.15(c)**).



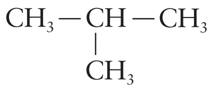
a Ball-and-stick model **b** Space-filling model **c**

Maren Slabaugh

FIGURE 11.15 (a and b) Perspective models of the propane molecule $CH_3CH_2CH_3$. (c) Propane is a common fuel for gas grills.

The fourth member of the series, butane, with molecular formula C_4H_{10}, can also be produced by removing a hydrogen atom (this time from propane) and adding a $—CH_3$. However, all the hydrogen atoms of propane are not geometrically equivalent, and more than one position is available for substitution. Replacing a hydrogen atom on one of the end carbons of propane with $—CH_3$ produces a butane molecule that has the structural formula

$CH_3—CH_2—CH_2—CH_3$. If, however, substitution is made on the central carbon atom of propane, the butane produced is



$$\begin{array}{ccccc} CH_3 & - & CH & - & CH_3 \\ & & | & & \\ & & CH_3 & & \end{array}$$

Notice that both butanes have the same molecular formula, C_4H_{10}. These two possible butanes are structural isomers because they have the same molecular formulas, but they have different atom-to-atom bonding sequences. The straight-chain isomer is called a **normal alkane** and the other is a **branched alkane** (see **Figure 11.16**).

normal alkane Any alkane in which all the carbon atoms are aligned in a continuous chain.

branched alkane An alkane in which at least one carbon atom is not part of a continuous chain.

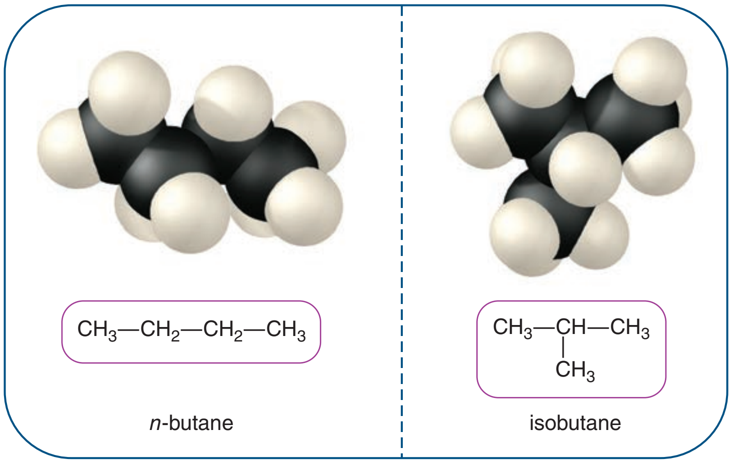


FIGURE 11.16 Space-filling models of the isomeric butanes.

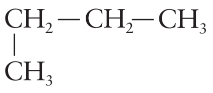
The number of possible structural isomers increases dramatically with the number of carbon atoms in an alkane, as shown in **Table 11.3**.

TABLE 11.3 Molecular Formulas and Possible Structural Isomers of Alkanes

Molecular Formula	Number of Possible Structural Isomers
C_4H_{10}	2
C_5H_{12}	3
C_6H_{14}	5
$C_{10}H_{22}$	75
$C_{20}H_{42}$	366,319
$C_{30}H_{62}$	4,111,846,763

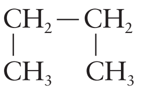
Example 11.3 Classifying Alkane Chains

Volatile short-chain alkanes can be produced by plant tissues. For example, certain species of pine are known for producing *n*-heptane. Classify the following alkanes as normal or branched.



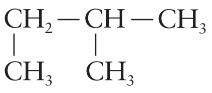
$$\begin{array}{ccccc} CH_2 & - & CH_2 & - & CH_3 \\ | & & & & \\ CH_3 & & & & \end{array}$$

a.



$$\begin{array}{ccc} CH_2 & - & CH_2 \\ | & & | \\ CH_3 & & CH_3 \end{array}$$

b.

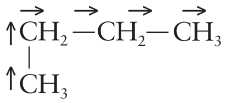


$$\begin{array}{ccccc} CH_2 & - & CH & - & CH_3 \\ | & & | & & \\ CH_3 & & CH_3 & & \end{array}$$

c.

Solution

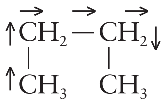
a. There is a continuous chain of carbon atoms.



$$\begin{array}{ccccc} \uparrow\overset{\rightarrow}{CH_2} & - & \overset{\rightarrow}{CH_2} & - & \overset{\rightarrow}{CH_3} \\ | & & & & \\ \uparrow CH_3 & & & & \end{array}$$

The structure could be written as $CH_3—CH_2—CH_2—CH_3$, showing that it is a straight-chain, or normal, alkane.

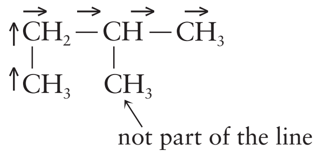
b. Even though the structure is bent, all four carbons can be connected by a continuous line.



$$\begin{array}{ccc} \uparrow\overset{\rightarrow}{CH_2} & \overset{\rightarrow}{-} & \overset{\rightarrow}{CH_2}\downarrow \\ | & & | \\ \uparrow CH_3 & & CH_3 \end{array}$$

This structure, too, could be written as $CH_3—CH_2—CH_2—CH_3$, with all carbons in a straight line. It is a normal alkane.

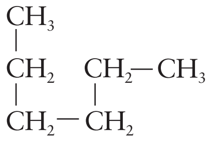
c. Connecting all carbons with a continuous line is not possible.



$$\begin{array}{lll} \uparrow\overrightarrow{CH_2} - & \overrightarrow{CH} - & \overrightarrow{CH_3} \\ \quad | & \;\, | & \\ \uparrow CH_3 & CH_3 & \end{array}$$

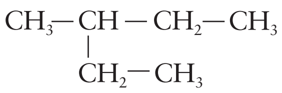
This is a branched alkane.

✔ **LEARNING CHECK 11.5** Classify the following as either normal or branched alkanes.



$$\begin{array}{ll} CH_3 & \\ | & \\ CH_2 & CH_2-CH_3 \\ | & | \\ CH_2- & CH_2 \end{array}$$

a.



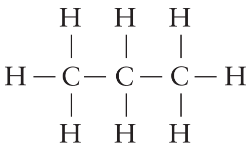
$$\begin{array}{l} CH_3-CH-CH_2-CH_3 \\ \qquad\;\; | \\ \qquad CH_2-CH_3 \end{array}$$

b.

11.6 Conformations of Alkanes

Learning Objective 7 Use structural formulas to determine whether compounds are structural isomers.

Remember that planar representations such as $CH_3—CH_2—CH_3$ or



$$\begin{array}{ccccccc} & & H & & H & & H & \\ & & | & & | & & | & \\ H & - & C & - & C & - & C & - & H \\ & & | & & | & & | & \\ & & H & & H & & H & \end{array}$$

are given with no attempt to accurately portray correct bond angles or molecular geometries. Structural formulas are usually written horizontally simply because it is convenient to do so. It is also important to know that actual organic molecules are in constant motion—twisting, turning, vibrating, and bending. Groups connected by a single bond are capable of rotating about that bond much like a wheel rotates around an axle (see **Figure 11.17**). As a result of such rotation about single bonds, a molecule can exist in many different orientations, called **conformations**. In a sample of butane containing billions of identical molecules, there are countless conformations present at any instant, and each conformation is rapidly changing into another. Two of the possible conformations of butane are shown in **Figure 11.18**. We must be sure to recognize that these different conformations do not represent different structural isomers. In each case, the four carbon atoms are bonded in a continuous (unbranched) chain. Since the order of bonding is not changed, the conformations correspond to the same molecule. Two structures would be structural isomers only if bonds had to be broken and remade to convert one into the other.

conformations The different arrangements of atoms in space achieved by rotation about single bonds.

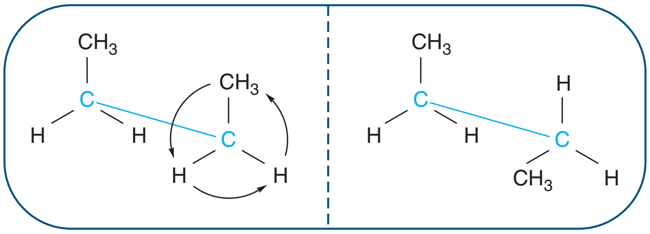


FIGURE 11.17 Rotation about single bonds (*n*-butane molecule).

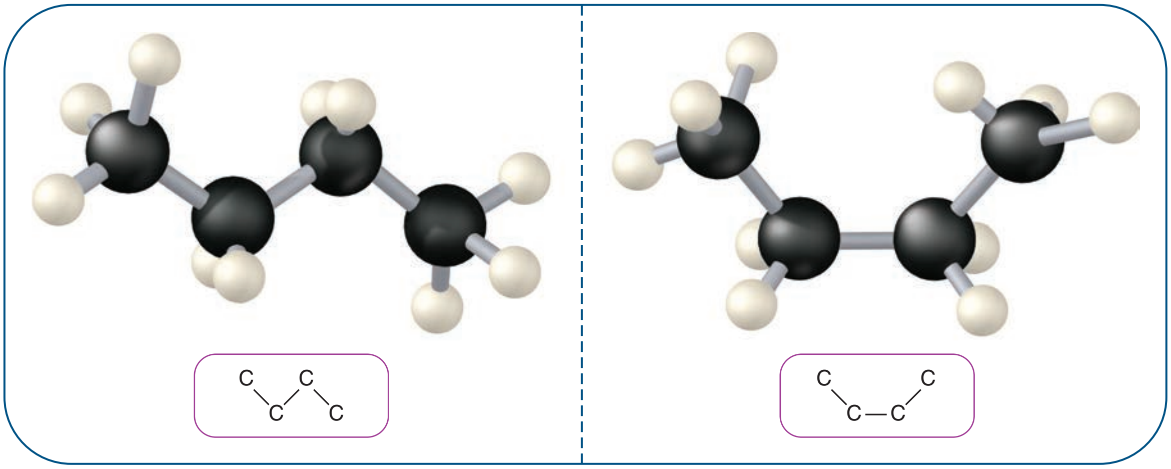
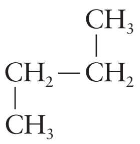


FIGURE 11.18 Perspective models and carbon skeletons of two conformations of *n*-butane.

Example 11.4 Identifying Structural Isomers

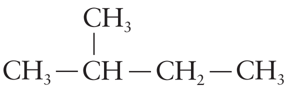
Which of the following pairs are structural isomers, and which are simply different representations of the same molecule?

a. $CH_3-CH_2-CH_2-CH_3$

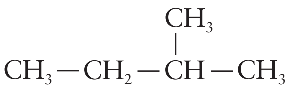


$$\begin{array}{ccc} & & CH_3 \\ & & | \\ CH_2 & - & CH_2 \\ | & & \\ CH_3 & & \end{array}$$

b.

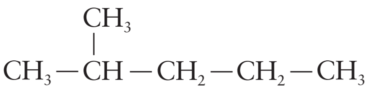


$$CH_3-\overset{CH_3}{\overset{|}{CH}}-CH_2-CH_3$$

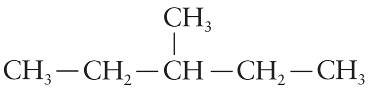


$$CH_3-CH_2-\overset{CH_3}{\overset{|}{CH}}-CH_3$$

c.



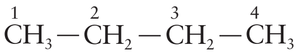
$$CH_3-\overset{CH_3}{\overset{|}{CH}}-CH_2-CH_2-CH_3$$



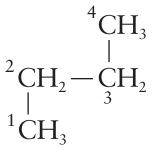
$$CH_3-CH_2-\overset{CH_3}{\overset{|}{CH}}-CH_2-CH_3$$

Solution

a. Same molecule: In both molecules, the four carbons are bonded in a continuous chain.

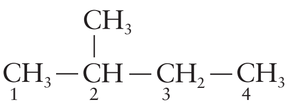


$$\overset{1}{CH_3}-\overset{2}{CH_2}-\overset{3}{CH_2}-\overset{4}{CH_3}$$

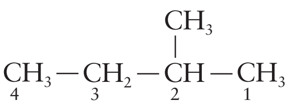


$$\begin{array}{ccc} & & {}^4CH_3 \\ & & | \\ {}^2CH_2 & - & \underset{3}{CH_2} \\ | & & \\ {}^1CH_3 & & \end{array}$$

b. Same molecule: In both molecules, there is a continuous chain of four carbons with a branch at position 2. The molecule has simply been turned around.

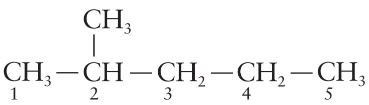


$$\underset{1}{CH_3}-\underset{2}{\overset{CH_3}{\overset{|}{CH}}}-\underset{3}{CH_2}-\underset{4}{CH_3}$$

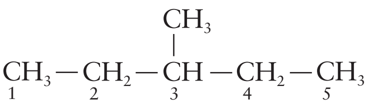


$$\underset{4}{CH_3}-\underset{3}{CH_2}-\underset{2}{\overset{CH_3}{\overset{|}{CH}}}-\underset{1}{CH_3}$$

c. Structural isomers: Both molecules have a continuous chain of five carbons, but the branch is located at different positions.



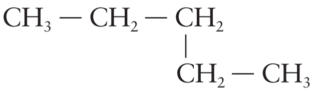
$$\underset{1}{CH_3}-\underset{2}{\overset{CH_3}{\overset{|}{CH}}}-\underset{3}{CH_2}-\underset{4}{CH_2}-\underset{5}{CH_3}$$



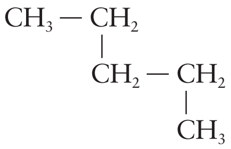
$$\underset{1}{CH_3}-\underset{2}{CH_2}-\underset{3}{\overset{CH_3}{\overset{|}{CH}}}-\underset{4}{CH_2}-\underset{5}{CH_3}$$

✔ **LEARNING CHECK 11.6** Which of the following pairs represent structural isomers, and which are simply the same compound?

a.

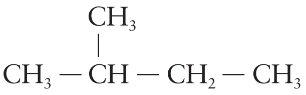


$$\begin{array}{ccccccc} CH_3 & - & CH_2 & - & CH_2 & & \\ & & & & | & & \\ & & & & CH_2 & - & CH_3 \end{array}$$

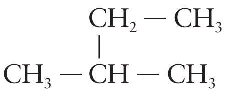


$$\begin{array}{ccccc} CH_3 & - & CH_2 & & \\ & & | & & \\ & & CH_2 & - & CH_2 \\ & & & & | \\ & & & & CH_3 \end{array}$$

b.

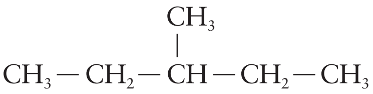


$$\begin{array}{ccccccc} & & CH_3 & & & & \\ & & | & & & & \\ CH_3 & - & CH & - & CH_2 & - & CH_3 \end{array}$$

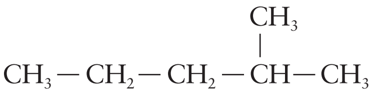


$$\begin{array}{ccccc} & & CH_2 & - & CH_3 \\ & & | & & \\ CH_3 & - & CH & - & CH_3 \end{array}$$

c.



$$\begin{array}{ccccccccc} & & & & CH_3 & & & & \\ & & & & | & & & & \\ CH_3 & - & CH_2 & - & CH & - & CH_2 & - & CH_3 \end{array}$$



$$\begin{array}{ccccccccc} & & & & & & CH_3 & & \\ & & & & & & | & & \\ CH_3 & - & CH_2 & - & CH_2 & - & CH & - & CH_3 \end{array}$$

11.7 Alkane Nomenclature

Learning Objective 8 Assign IUPAC names and draw structural formulas for alkanes.

When only a relatively few organic compounds were known, chemists gave them what are today called trivial or common names, such as methane (see **Figure 11.19**), ethane, propane (see **Figure 11.20**), and butane. The names for the larger alkanes were derived from the Greek prefixes that indicate the number of carbon atoms in the molecule. Thus, *pent*ane contains five carbons, *hex*ane has six, *hep*tane has seven, and so forth, as shown in **Table 11.4**.

Antranias/4323 images/Pixabay

FIGURE 11.19 Microorganisms in the guts of cows produce some of the methane in Earth's atmosphere.

Karol Franks/Moment/Getty Images

FIGURE 11.20 Hot air balloons use liquid propane to fuel their flight, keeping the balloon filled with air near 250°F.

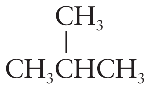
TABLE 11.4 Names of Alkanes

Number of Carbon Atoms	Name	Molecular Formula	Structure of Normal Isomer
1	methane	CH_4	CH_4
2	ethane	C_2H_6	CH_3CH_3
3	propane	C_3H_8	$CH_3CH_2CH_3$
4	butane	C_4H_{10}	$CH_3CH_2CH_2CH_3$
5	pentane	C_5H_{12}	$CH_3CH_2CH_2CH_2CH_3$
6	hexane	C_6H_{14}	$CH_3CH_2CH_2CH_2CH_2CH_3$
7	heptane	C_7H_{16}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_3$
8	octane	C_8H_{18}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$
9	nonane	C_9H_{20}	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$
10	decane	$C_{10}H_{22}$	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$

As more compounds and isomers were discovered, however, it became increasingly difficult to devise unique names and much more difficult to commit them to memory. Obviously, a systematic method was needed. Such a method is now in use, but so are several common methods.

The names for the two isomeric butanes (*n*-butane and isobutane) illustrate the important features of the common nomenclature system used for alkanes. The stem *but-* indicates that four carbons are present in the molecule. The *-ane* ending signifies the alkane family. The prefix *n-* indicates that all carbons form an unbranched chain. The prefix *iso-* refers to compounds in which all carbons except one are in a continuous chain and in which that one carbon is branched from a next-to-the-end carbon, as shown:

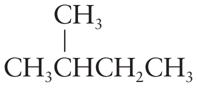
$CH_3CH_2CH_2CH_3$
n-butane



$$CH_3\overset{\overset{CH_3}{|}}{C}HCH_3$$

isobutane

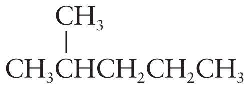
$CH_3CH_2CH_2CH_2CH_3$
n-pentane



$$CH_3\overset{\overset{CH_3}{|}}{C}HCH_2CH_3$$

isopentane

$CH_3CH_2CH_2CH_2CH_2CH_3$
n-hexane

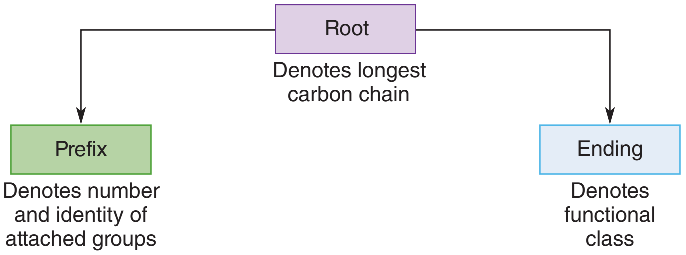


$$CH_3\overset{\overset{CH_3}{|}}{C}HCH_2CH_2CH_3$$

isohexane

This common naming system has limitations. Pentane has three isomers, and hexane has five. The more complicated the compound, the greater the number of isomers, and the greater the number of special prefixes needed to name all the isomers. It would be extremely difficult and time-consuming to try to identify each of the 75 isomeric alkanes containing 10 carbon atoms by a unique prefix or name.

To devise a system of nomenclature that could be used for even the most complicated compounds, committees of chemists have met periodically since 1892. The system resulting from these meetings is called the IUPAC (International Union of Pure and Applied Chemistry) system. This system is much the same for all classes of organic compounds. The IUPAC name for an organic compound consists of three component parts:


Root
Denotes longest carbon chain
Prefix
Denotes number and identity of attached groups
Ending
Denotes functional class

The *root* of the IUPAC name specifies the longest continuous chain of carbon atoms in the compound. The roots for the first 10 normal hydrocarbons are based on the names given in **Table 11.4**: C_1 *meth-,* C_2 *eth-,* C_3 *prop-,* C_4 *but-,* C_5 *pent-,* C_6 *hex-,* C_7 *hept-,* C_8 *oct-,* C_9 *non-,* and C_{10} *dec-*.

The *ending* of an IUPAC name specifies the functional class or the major functional group of the compound. The ending *-ane* specifies an alkane. Each of the other functional classes has a characteristic ending; for example, *-ene* is the ending for alkenes, and the *-ol* ending designates alcohols.

Prefixes are used to specify the identity, number, and location of atoms or groups of atoms that are attached to the longest carbon chain. **Table 11.5** lists several common carbon-containing groups referred to as **alkyl groups**. Each alkyl group is a collection of atoms that can be thought of as an alkane minus one hydrogen atom. Alkyl groups are named simply by dropping *-ane* from the name of the corresponding alkane and replacing it with *-yl*. For example, CH_3— is called a methyl group and $CH_3—CH_2$— an ethyl group:

alkyl group A group differing by one hydrogen from an alkane.

CH_4	$CH_3—CH_3$	$CH_3—$	$CH_3—CH_2—$
methane	ethane	methyl group	ethyl group

Two different alkyl groups can be derived from propane, depending on which hydrogen is removed. Removal of a hydrogen from an end carbon results in a propyl group:

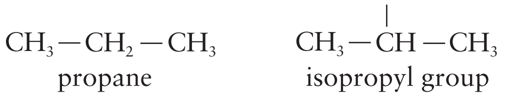
$CH_3—CH_2—CH_3$	$CH_3—CH_2—CH_2—$
propane	propyl group

TABLE 11.5 Common Alkyl Groups

Parent Alkane	Structure of Parent Alkane	Structure of Alkyl Group	Name of Alkyl Group
Methane	CH_4	CH_3-	methyl
Ethane	CH_3CH_3	CH_3CH_2-	ethyl
Propane	$CH_3CH_2CH_3$	$CH_3CH_2CH_2-$	propyl
		$CH_3\overset{\vert}{C}HCH_3$	isopropyl
n-butane	$CH_3CH_2CH_2CH_3$	$CH_3CH_2CH_2CH_2-$	butyl
		$CH_3CH_2\overset{\vert}{C}HCH_3$	*sec*-butyl (secondary-butyl)[a]
Isobutane	$CH_3\overset{\overset{CH_3}{\vert}}{C}HCH_3$	$CH_3\overset{\overset{CH_3}{\vert}}{C}HCH_2-$	isobutyl
		$CH_3\underset{\vert}{\overset{\overset{CH_3}{\vert}}{C}}CH_3$	*t*-butyl (tertiary-butyl)[a]

[a] For an explanation of *secondary* and *tertiary*, see **Section 13.2**.

Removal of a hydrogen from the center carbon results in an isopropyl group:



$$\underset{\text{propane}}{CH_3-CH_2-CH_3} \qquad \underset{\text{isopropyl group}}{CH_3-\overset{\vert}{CH}-CH_3}$$

An isopropyl group also can be represented by $(CH_3)_2CH-$. As shown in **Table 11.5**, four butyl groups can be derived from butane, two from the straight-chain, or normal, butane, and two from the branched-chain isobutane (see **Figure 11.21**). A number of nonalkyl groups are also commonly used in naming organic compounds (see **Table 11.6**).

The following steps are useful when the IUPAC name of an alkane is written on the basis of its structural formula:

Step 1. *Name the longest chain.* The longest continuous carbon-atom chain is chosen as the basis for the name. The names are those given in **Table 11.4**.

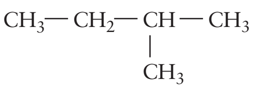
Wavebreakmedia/iStock/Getty Images

FIGURE 11.21 Camping wouldn't be nearly as fun without canister stoves, which typically use an isobutane–propane mixture as fuel.

Example 11.5 Identifying Longest Chains

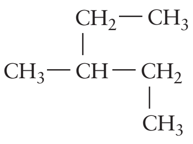
Identify the longest chain in the following:

a.



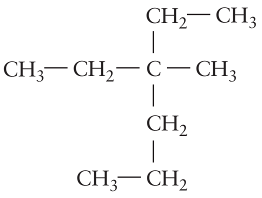
$$CH_3-CH_2-\underset{\underset{CH_3}{\vert}}{CH}-CH_3$$

b.



$$CH_3-\overset{\overset{CH_2-CH_3}{\vert}}{CH}-\underset{\underset{CH_3}{\vert}}{CH_2}$$

c.



$$CH_3-CH_2-\underset{\underset{\underset{CH_3-CH_2}{\vert}}{\underset{CH_2}{\vert}}}{\overset{\overset{CH_2-CH_3}{\vert}}{C}}-CH_3$$

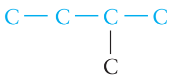
TABLE 11.6 Common Nonalkyl Groups

Group	Name
$-F$	fluoro
$-Cl$	chloro
$-Br$	bromo
$-I$	iodo
$-NO_2$	nitro
$-NH_2$	amino

Solution

The longest continuous chains are shown in color.

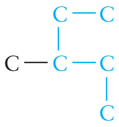
a.



$$\begin{array}{ccccccc} \mathrm{C} & - & \mathrm{C} & - & \mathrm{C} & - & \mathrm{C} \\ & & & & | & & \\ & & & & \mathrm{C} & & \end{array}$$

There are four carbons in the longest chain. This compound is a butane.

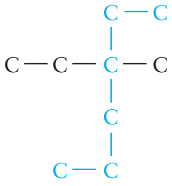
b.



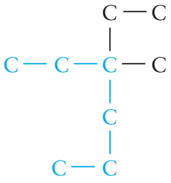
$$\begin{array}{ccccc} & & \mathrm{C} & - & \mathrm{C} \\ & & | & & \\ \mathrm{C} & - & \mathrm{C} & - & \mathrm{C} \\ & & & & | \\ & & & & \mathrm{C} \end{array}$$

With five carbons in the longest chain, this compound is a pentane.

c.



$$\begin{array}{ccccccc} & & & & \mathrm{C} & - & \mathrm{C} \\ & & & & | & & \\ \mathrm{C} & - & \mathrm{C} & - & \mathrm{C} & - & \mathrm{C} \\ & & & & | & & \\ & & & & \mathrm{C} & & \\ & & & & | & & \\ & & \mathrm{C} & - & \mathrm{C} & & \end{array}$$

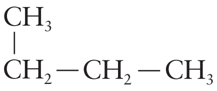


$$\begin{array}{ccccccc} & & & & \mathrm{C} & - & \mathrm{C} \\ & & & & | & & \\ \mathrm{C} & - & \mathrm{C} & - & \mathrm{C} & - & \mathrm{C} \\ & & & & | & & \\ & & & & \mathrm{C} & & \\ & & & & | & & \\ & & \mathrm{C} & - & \mathrm{C} & & \end{array}$$

Often there is more than one way to designate the longest chain. Either way, in this case, the compound is a hexane.

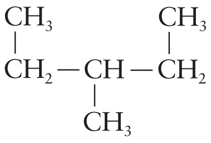
✔ LEARNING CHECK 11.7 Identify the longest carbon chain in the following:

a.



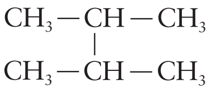
$$\begin{array}{ccccc} \mathrm{CH_3} & & & & \\ | & & & & \\ \mathrm{CH_2} & - & \mathrm{CH_2} & - & \mathrm{CH_3} \end{array}$$

b.



$$\begin{array}{ccccc} \mathrm{CH_3} & & & & \mathrm{CH_3} \\ | & & & & | \\ \mathrm{CH_2} & - & \mathrm{CH} & - & \mathrm{CH_2} \\ & & | & & \\ & & \mathrm{CH_3} & & \end{array}$$

c.



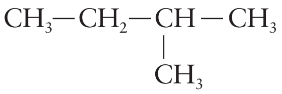
$$\begin{array}{ccccc} \mathrm{CH_3} & - & \mathrm{CH} & - & \mathrm{CH_3} \\ & & | & & \\ \mathrm{CH_3} & - & \mathrm{CH} & - & \mathrm{CH_3} \end{array}$$

Step 2. *Number the longest chain.* The carbon atoms in the longest chain are numbered consecutively from the end that will give the lowest possible number to any carbon to which a group is attached.

Example 11.6 Numbering Longest Chains

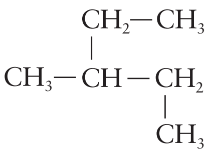
Correctly number the carbons in the longest chains of the following structures:

a.



$$\begin{array}{ccccccc} \mathrm{CH_3} & - & \mathrm{CH_2} & - & \mathrm{CH} & - & \mathrm{CH_3} \\ & & & & | & & \\ & & & & \mathrm{CH_3} & & \end{array}$$

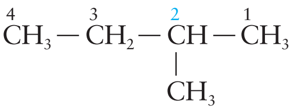
b.



$$\begin{array}{ccccc} & & \mathrm{CH_2} & - & \mathrm{CH_3} \\ & & | & & \\ \mathrm{CH_3} & - & \mathrm{CH} & - & \mathrm{CH_2} \\ & & & & | \\ & & & & \mathrm{CH_3} \end{array}$$

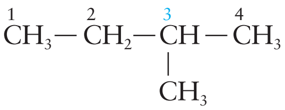
Solution

a. Numbering the chain from the right gives the lowest number for the position of the —CH_3 group.



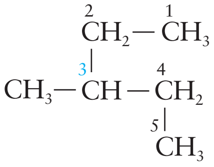
$$\begin{array}{ccccccc} \overset{4}{\mathrm{CH_3}} & - & \overset{3}{\mathrm{CH_2}} & - & \overset{2}{\mathrm{CH}} & - & \overset{1}{\mathrm{CH_3}} \\ & & & & | & & \\ & & & & \mathrm{CH_3} & & \end{array}$$

and not

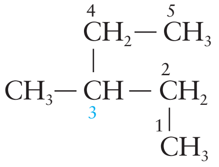


$$\begin{array}{ccccccc} \overset{1}{\mathrm{CH_3}} & - & \overset{2}{\mathrm{CH_2}} & - & \overset{3}{\mathrm{CH}} & - & \overset{4}{\mathrm{CH_3}} \\ & & & & | & & \\ & & & & \mathrm{CH_3} & & \end{array}$$

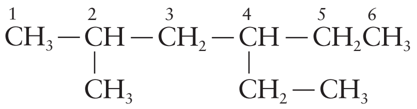
b. Sometimes there is more than one way to correctly number the longest chain.



the chain may also be numbered

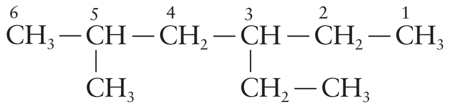


If two or more alkyl groups are attached to the longest chain and more than one numbering sequence is possible, the chain is numbered to get the lowest series of numbers. An easy way to follow this rule is to number from the end of the chain nearest a branch:

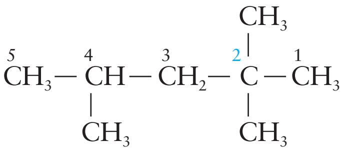

$CH_3-CH(CH_3)-CH_2-CH(CH_2-CH_3)-CH_2CH_3$

Groups are located at positions 2 and 4

and not

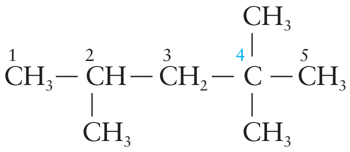

$CH_3-CH(CH_3)-CH_2-CH(CH_2-CH_3)-CH_2-CH_3$

Groups are located at positions 3 and 5


$CH_3-CH(CH_3)-CH_2-C(CH_3)_2-CH_3$

Groups are located at positions 2,2,4

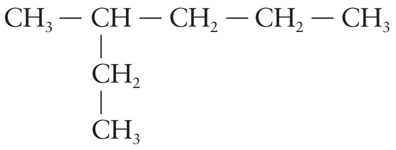
and not

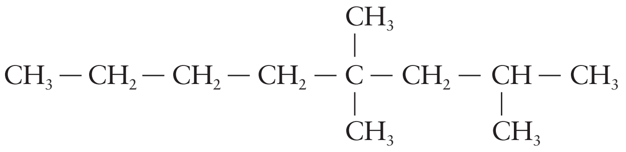

$CH_3-CH(CH_3)-CH_2-C(CH_3)_2-CH_3$

Groups are located at positions 2,4,4

Here, a difference occurs with the second number in the sequence, so positions 2,2,4 is the lowest series and is used rather than positions 2,4,4.

✔ **LEARNING CHECK 11.8** Decide how to correctly number the longest chain in the following according to IUPAC rules:

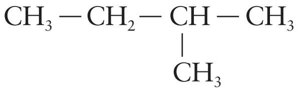
a. 
$CH_3-CH(CH_2-CH_3)-CH_2-CH_2-CH_3$

b. 
$CH_3-CH_2-CH_2-CH_2-C(CH_3)_2-CH_2-CH(CH_3)-CH_3$

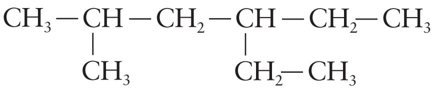
Step 3. *Locate and name the attached alkyl groups.* Each group is located by the number of the carbon atom to which it is attached on the chain.

Example 11.7 Naming Alkyl Groups

Locate and name the attached alkyl groups in the following structures:

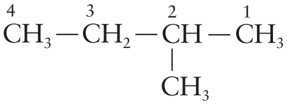
a. 
$CH_3-CH_2-CH(CH_3)-CH_3$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

b. 

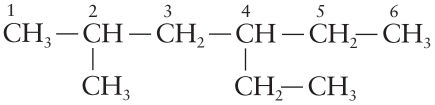
$$CH_3-\underset{\displaystyle CH_3}{\underset{|}{CH}}-CH_2-\underset{\displaystyle CH_2-CH_3}{\underset{|}{CH}}-CH_2-CH_3$$

Solution

a. 

$$\overset{4}{CH_3}-\overset{3}{CH_2}-\underset{\displaystyle CH_3}{\underset{|}{\overset{2}{CH}}}-\overset{1}{CH_3}$$

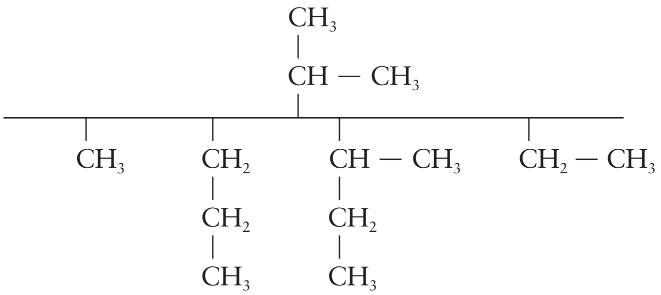
The attached group is located on carbon 2 of the chain, and it is a methyl group.

b. 

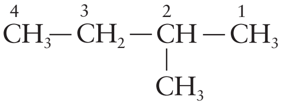
$$\overset{1}{CH_3}-\underset{\displaystyle CH_3}{\underset{|}{\overset{2}{CH}}}-\overset{3}{CH_2}-\underset{\displaystyle CH_2-CH_3}{\underset{|}{\overset{4}{CH}}}-\overset{5}{CH_2}-\overset{6}{CH_3}$$

The one-carbon group at position 2 is a methyl group. The two-carbon group at position 4 is an ethyl group.

✔ **LEARNING CHECK 11.9** Identify the alkyl groups attached to the horizontal line, which symbolizes a long carbon chain. Refer to **Table 11.5**, if necessary.



Step 4. *Combine the longest chain and the branches into the name.* The position and the name of the attached alkyl group are added to the name of the longest chain and written as one word:

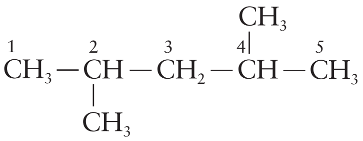


$$\overset{4}{CH_3}-\overset{3}{CH_2}-\underset{\displaystyle CH_3}{\underset{|}{\overset{2}{CH}}}-\overset{1}{CH_3}$$

2-methylbutane

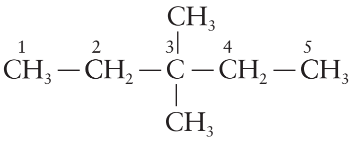
Additional steps are needed when more than one alkyl group is attached to the longest chain.

Step 5. *Indicate the number and position of attached alkyl groups.* If two or more of the same alkyl group occur as branches, the number of them is indicated by the prefixes *di*-, *tri*-, *tetra*-, *penta*-, etc., and the location of each is again indicated by a number. These position numbers, separated by commas, are put just before the name of the group, with hyphens before and after the numbers when necessary:



$$\overset{1}{CH_3}-\underset{\displaystyle CH_3}{\underset{|}{\overset{2}{CH}}}-\overset{3}{CH_2}-\overset{\displaystyle CH_3}{\overset{4|}{CH}}-\overset{5}{CH_3}$$

2,4-dimethylpentane



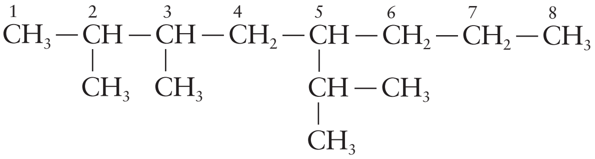
$$\overset{1}{CH_3}-\overset{2}{CH_2}-\underset{\displaystyle CH_3}{\underset{|}{\overset{\displaystyle CH_3}{\overset{3|}{C}}}}-\overset{4}{CH_2}-\overset{5}{CH_3}$$

3,3-dimethylpentane

If two or more *different* alkyl groups are present, their names are alphabetized and added to the name of the basic alkane, again as one word. For purposes of

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

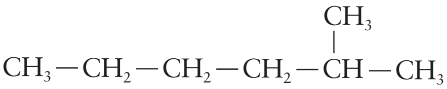
alphabetizing, the prefixes *di-, tri-,* and so on are ignored, as are the italicized prefixes secondary *(sec)* and tertiary *(t)*. The prefix *iso-* is an exception and is used for alphabetizing:



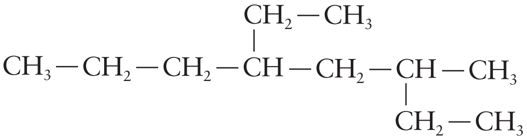
$$\begin{array}{ccccccccccccccc}
\overset{1}{CH_3} & - & \overset{2}{CH} & - & \overset{3}{CH} & - & \overset{4}{CH_2} & - & \overset{5}{CH} & - & \overset{6}{CH_2} & - & \overset{7}{CH_2} & - & \overset{8}{CH_3} \\
 & & | & & | & & & & | & & & & & & \\
 & & CH_3 & & CH_3 & & & & CH-CH_3 & & & & & & \\
 & & & & & & & & | & & & & & & \\
 & & & & & & & & CH_3 & & & & & &
\end{array}$$

5-isopropyl-2,3-dimethyloctane

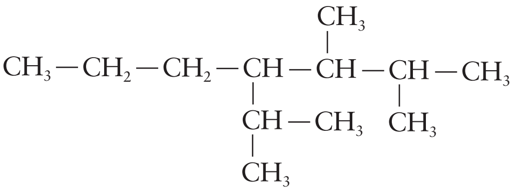
✔ LEARNING CHECK 11.10 Give the correct IUPAC name for each of the following:

a. 

$$\begin{array}{ccccccccccc}
 & & & & & & & & CH_3 & & \\
 & & & & & & & & | & & \\
CH_3 & - & CH_2 & - & CH_2 & - & CH_2 & - & CH & - & CH_3
\end{array}$$

b. 

$$\begin{array}{ccccccccccc}
 & & & & & & CH_2-CH_3 & & & & \\
 & & & & & & | & & & & \\
CH_3 & - & CH_2 & - & CH_2 & - & CH & - & CH_2 & - & CH-CH_3 \\
 & & & & & & & & & & | \\
 & & & & & & & & & & CH_2-CH_3
\end{array}$$

c. 

$$\begin{array}{ccccccccccccc}
 & & & & & & & & CH_3 & & & & \\
 & & & & & & & & | & & & & \\
CH_3 & - & CH_2 & - & CH_2 & - & CH & - & CH & - & CH & - & CH_3 \\
 & & & & & & | & & & & | & & \\
 & & & & & & CH-CH_3 & & & & CH_3 & & \\
 & & & & & & | & & & & & & \\
 & & & & & & CH_3 & & & & & &
\end{array}$$

Naming compounds is a very important skill, as is the reverse process of using IUPAC nomenclature to specify a structural formula. The two processes are very similar. To obtain a formula from a name, determine the longest chain, number the chain, and add any attached groups.

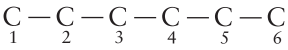
Example 11.8 Drawing Condensed Structural Formulas

Since there are thousands of biological and medicinal compounds, being able to draw and name structures is an important skill, leaving no ambiguity concerning which chemical compound is being used.

Draw a condensed structural formula for 3-ethyl-2-methylhexane.

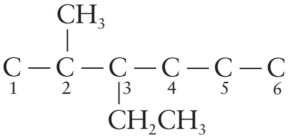
Solution

Use the last part of the name to determine the longest chain. Draw a chain of six carbons. Then, number the carbon atoms.



$$\underset{1}{C}-\underset{2}{C}-\underset{3}{C}-\underset{4}{C}-\underset{5}{C}-\underset{6}{C}$$

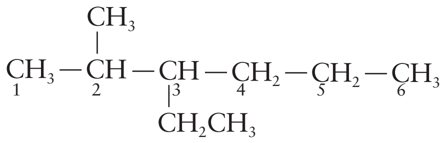
Attach a methyl group at position 2 and an ethyl group at position 3.



$$\begin{array}{ccccccccccc}
 & & CH_3 & & & & & & & & \\
 & & | & & & & & & & & \\
\underset{1}{C} & - & \underset{2}{C} & - & \underset{3}{C} & - & \underset{4}{C} & - & \underset{5}{C} & - & \underset{6}{C} \\
 & & & & | & & & & & & \\
 & & & & CH_2CH_3 & & & & & &
\end{array}$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Complete the structure by adding enough hydrogen atoms so that each carbon has four bonds.



$$\underset{1}{CH_3}-\overset{\overset{\displaystyle CH_3}{|}}{\underset{2}{CH}}-\underset{\underset{\displaystyle CH_2CH_3}{|3}}{CH}-\underset{4}{CH_2}-\underset{5}{CH_2}-\underset{6}{CH_3}$$

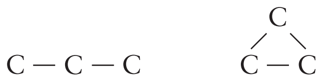
✔ **LEARNING CHECK 11.11** Draw a condensed structural formula for each of the following compounds:

a. 2,2,4-trimethylpentane
b. 3-isopropylhexane
c. 3-ethyl-2,4-dimethylheptane

11.8 Cycloalkanes

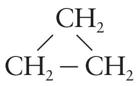
Learning Objective 9 Assign IUPAC names and draw structural formulas for cycloalkanes.

From what we have said so far, the formula C_3H_6 cannot represent an alkane. Not enough hydrogens are present to allow each carbon to form four bonds, unless there are multiple bonds. For example, the structural formula $CH_3—CH{=}CH_2$ fits the molecular formula but cannot represent an alkane because of the double bond. The C_3H_6 formula does become acceptable for an alkane if the carbon atoms form a ring, or cyclic, structure rather than the open-chain structure shown:



Open chain Cyclic

The resulting saturated cyclic compound, called cyclopropane, has the structural formula



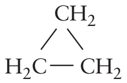
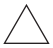
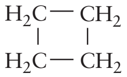
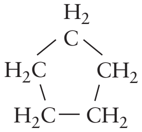
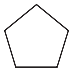
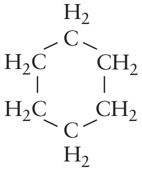
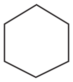
cycloalkane An alkane in which carbon atoms form a ring.

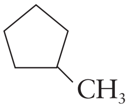
Alkanes containing rings of carbon atoms are called **cycloalkanes**. Like the other alkanes, cycloalkanes are not found in human cells. However, several important molecules in human cells do contain rings of five or six atoms, and the study of cycloalkanes will help you better understand the chemical behavior of these complex molecules.

According to IUPAC rules, cycloalkanes are named by placing the prefix *cyclo-* before the name of the corresponding alkane with the same number of carbon atoms. Chemists often abbreviate the structural formulas for cycloalkanes and draw them as geometric figures (triangles, squares, etc.) in which each corner represents a carbon atom. The hydrogens are omitted (see **Table 11.7**). It is important to remember that each carbon atom still possesses four bonds, and that hydrogen is assumed to be bonded to the carbon atoms unless something else is indicated. When substituted cycloalkanes (those with attached groups) are named, the position of a single attached group does not need to be specified in the name because all positions in the ring are equivalent. However, when two or more groups are attached, their positions of attachment are indicated by numbers, just as they were for alkanes. The ring numbering begins with the carbon attached to the first group alphabetically and proceeds around the ring in the direction that will give the lowest numbers for the locations of the other attached groups.

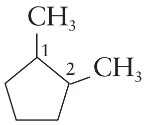
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

TABLE 11.7 Structural Formulas and Symbols for Common Cycloalkanes

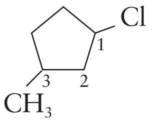
Name	Structural Formula	Condensed Formula
Cyclopropane		
Cyclobutane		
Cyclopentane		
Cyclohexane		



methylcyclopentane



1,2-dimethylcyclopentane
not 1,5-dimethylcyclopentane

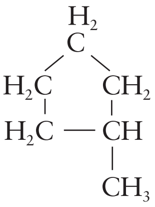


1-chloro-3-methylcyclopentane
not 1-chloro-4-methylcyclopentane
not 3-chloro-1-methylcyclopentane

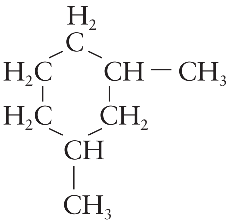
Example 11.9 Naming Cycloalkanes

Represent each of the following cycloalkanes by a geometric figure, and name each compound:

a.

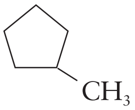


b.

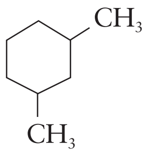


Solution

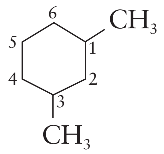
a. A pentagon represents a five-membered ring, which is called cyclopentane. This compound has a methyl group attached, so the name is methylcyclopentane. The position of a single alkyl group is not indicated by a number because the positions of all carbons in the ring are equivalent.



b. A hexagon represents a six-carbon ring, which is called cyclohexane. Two methyl groups are attached; thus we have a dimethylcyclohexane.

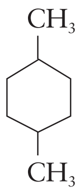


However, the positions of the two alkyl groups must be indicated. The ring is numbered beginning with a carbon to which a methyl group is attached, counting in the direction giving the lowest numbers. The correct name is 1,3-dimethylcyclohexane. Notice that a reverse numbering beginning at the same carbon would have given 1,5-dimethylcyclohexane. The number 3 in the correct name is lower than the 5 in the incorrect name.

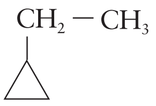


✔ **LEARNING CHECK 11.12** Give each of the following compounds the correct IUPAC name:

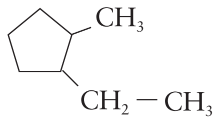
a.



b.



c.



11.9 The Shape of Cycloalkanes

Learning Objective 10 Name and draw structural formulas for *cis-trans* isomers of cycloalkanes.

Recall from **Section 11.5** that a tetrahedral orientation of bonds with bond angles of 109.5° is characteristic of carbon atoms that form four single bonds. A tetrahedral arrangement is the most stable because it results in the least crowding of the atoms. In certain cycloalkanes, however, a tetrahedral arrangement for all carbon-to-carbon bonds is not possible. For example, the bond angles between adjacent carbon–carbon bonds in planar cyclopropane molecules must be 60° (see **Figure 11.22**). In cyclobutane, they are close to 90°. As a result, cyclopropane and cyclobutane rings are much less stable than compounds with bond angles of about 109°. Both cyclobutane and cyclopentane bend slightly from a planar structure to reduce the crowding of hydrogen atoms (**Figure 11.22**). In larger cycloalkanes, the bonds to carbon atoms can be tetrahedrally arranged only when the carbon atoms do not lie in the same plane. For example, cyclohexane can assume several nonplanar shapes. The chair and boat forms, where all the bond angles are 109.5°, are shown in **Figure 11.22**.

The free rotation that can take place around C—C single bonds in alkanes (see **Section 11.6**) is not possible for the C—C bonds of cycloalkanes. The ring structure allows bending or puckering but prevents free rotation (see **Figure 11.23**). Any rotation of one carbon atom 180° relative to an adjacent carbon atom in a cycloalkane would require a single carbon–carbon bond to be broken somewhere in the ring. The breaking of such bonds would require a large amount of energy.

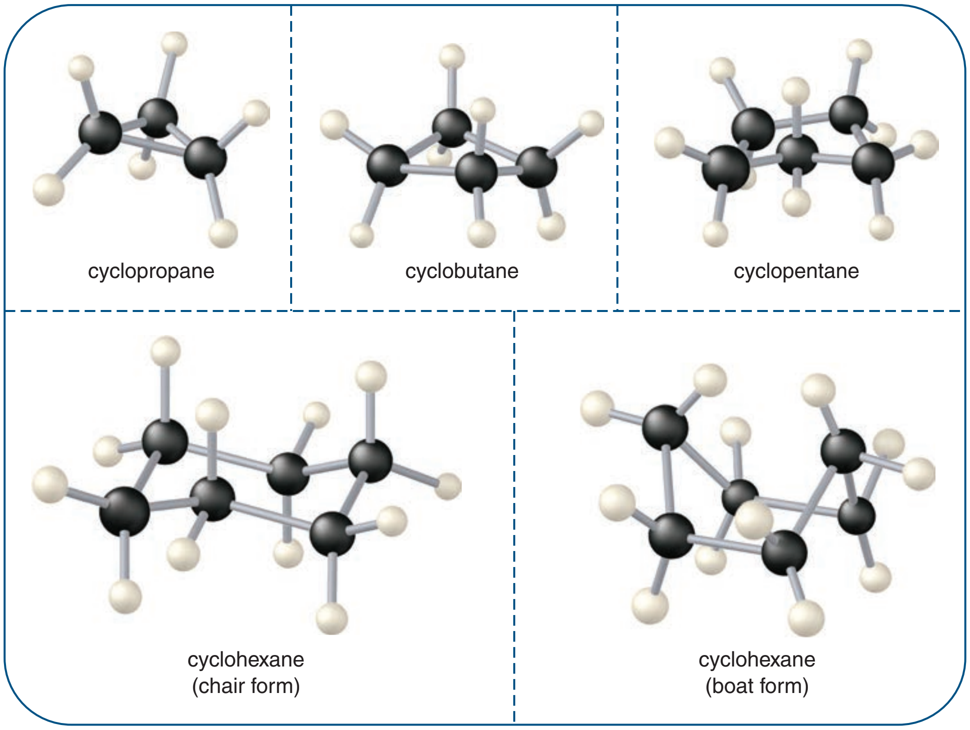

cyclopropane
cyclobutane
cyclopentane
cyclohexane (chair form)
cyclohexane (boat form)

FIGURE 11.22 Ball-and-stick models for common cycloalkanes.

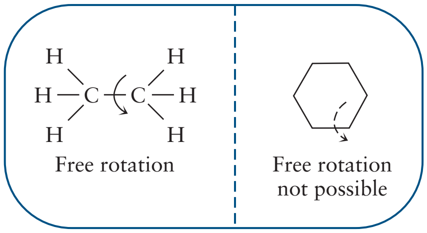

H
H
H
C
C
H
H
H
Free rotation
Free rotation not possible

FIGURE 11.23 Rotation about C—C single bonds occurs in open-chain compounds but not within rings.

The lack of free rotation around C—C bonds in disubstituted cycloalkanes leads to an extremely important kind of isomerism called *stereoisomerism.* Two different compounds that have the same molecular formula and the same structural formula but different spatial arrangements of atoms are called **stereoisomers**. For example, consider a molecule of 1,2-dimethylcyclopentane. The cyclopentane ring is drawn in **Figure 11.24** as a planar pentagon with the heavy lines indicating that two of the carbons are in front as one views the structure. The groups attached to the ring project above or below the plane of the ring. Two stereoisomers are possible: Either both groups may project in the same direction from the plane, or they may project in opposite directions from the plane of the ring. Since the methyl groups cannot rotate from one side of the ring to the other, molecules of the two compounds represented in **Figure 11.24** are distinct.

stereoisomers Compounds with the same structural formula but different spatial arrangements of atoms.

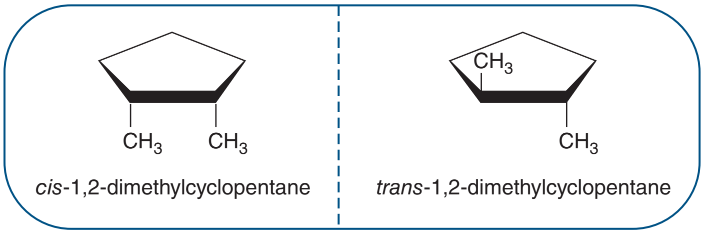

CH_3
CH_3
cis-1,2-dimethylcyclopentane
CH_3
CH_3
trans-1,2-dimethylcyclopentane

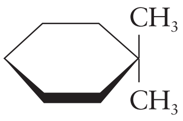
FIGURE 11.24 Two *cis-trans* isomers of 1,2-dimethylcyclopentane.

These two compounds have physical and chemical properties that are quite different and therefore can be separated from each other. Stereoisomers of this type, in which the spatial arrangement or geometry of their groups is maintained by rings, are called ***cis-trans* isomers**. The prefix ***cis-*** denotes the isomer in which both groups are on the same side of the ring, and ***trans-*** denotes the isomer in which they are on opposite sides. To exist as *cis-trans* isomers, a disubstituted cycloalkane must be bound to groups at two different carbons of the ring. For example, there are no *cis-trans* isomers of 1,1-dimethylcyclohexane:

***cis-trans* isomers** Molecules with restricted rotation around C—C bonds that differ in the three-dimensional arrangements of their atoms in space and not in the order of linkage of atoms.

cis- On the same side (as applied to *cis-trans* isomers.

trans- On opposite sides (as applied to *cis-trans* isomers.



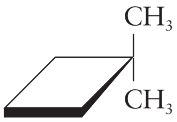
Example 11.10 Identifying *Cis-Trans* Isomers

Isomerism often results in compounds with distinct biological properties and roles.

Name and draw structural formulas for all the isomers of dimethylcyclobutane. Indicate which ones are *cis-trans* isomers.

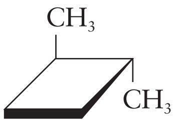
Solution

There are three possible locations for the two methyl groups: positions 1,1, positions 1,2, and positions 1,3.



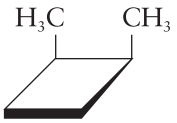
1,1-dimethylcyclobutane

Cis-trans isomerism is not possible in this case with the two groups bound to the same carbon of the ring



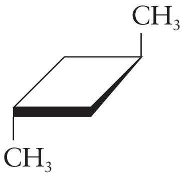
trans-1,2-dimethylcyclobutane

Two groups on opposite sides of the planar ring

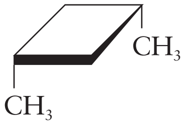


cis-1,2-dimethylcyclobutane

Two groups on the same side of the ring



trans-1,3-dimethylcyclobutane

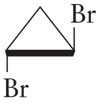


cis-1,3-dimethylcyclobutane

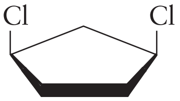
✔ LEARNING CHECK 11.13

a. Identify each of the following cycloalkanes as a *cis-* or *trans-* compound:

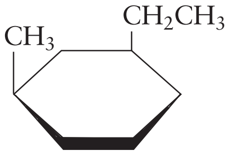
(1)



(2)



(3)



b. Draw the structural formula for *cis*-1,2-dichlorocyclobutane.

HEALTH CONNECTIONS 11.2

Take Care of Dry Skin

Healthy, normal human skin is kept moist by natural body oils contained in sebum, a secretion of the skin's sebaceous glands. The oily sebum helps the epidermis, or outer layer of the skin, retain the 10–30% of water it normally contains. However, some people suffer from skin that is naturally dry, or dry because of aging or contact with materials like paint thinner that dissolve and remove the sebum. Such individuals may find some relief by using OTC products called *moisturizers.*

Two types of skin moisturizers are commonly available. One type, which behaves like natural sebum, contains nonpolar oily substances that form a barrier and prevent water from passing through and evaporating from the skin. These barrier-forming products often contain combinations of materials from various sources, including mineral oil and petroleum jelly from petroleum; vegetable oils such as apricot oil; sesame seed oil, palm kernel oil, olive oil, and safflower oil; and lanolin, an animal fat from sheep oil glands and wool. While they effectively keep water from leaving the skin, these products are somewhat messy to use and leave the skin feeling greasy.

A second, more popular type of moisturizer works by attracting water from the air and skin. These products form a water-rich layer that adheres to the skin without giving it a greasy feel. The substances that attract water are called *humectants*, and are compounds capable of forming hydrogen bonds with water. Some examples of humectants used in products of this type are glycerol, urea, lactic acid, and propylene glycol.

If you are shopping for a moisturizer, remember that the main characteristic you should look for in a product is the ability to form a barrier to prevent water evaporation, or the ability to act as a humectant. Some expensive products advertise that in addition to moisturizing, they also beautify the skin and even reverse aging because they contain proteins such as collagen and elastin, vitamins, hormones, or even DNA. It is unlikely that such substances can pass through the epidermis of the skin in sufficient amounts to provide the advertised benefits.

J.Schuyler

Alkane products marketed to soften and protect the skin.

11.10 Physical Properties of Alkanes

Learning Objective 11 Describe the key physical properties of alkanes.

Since alkanes are composed of nonpolar carbon–carbon and carbon–hydrogen bonds, they are nonpolar molecules. Alkanes have lower melting and boiling points than other organic compounds of comparable molecular weight (see **Table 11.8**). This is because their nonpolar molecules exert very weak attractions for each other. Alkanes are odorless compounds.

The normal, or straight-chain, alkanes make up what is called a **homologous series**. This term describes any series of compounds in which each member differs from a previous member only by having an additional $—CH_2—$ unit. The physical and chemical properties of compounds making up a homologous series are usually closely related and vary in a systematic and predictable way. For example, the boiling points of normal alkanes increase smoothly as the length of the carbon chain increases (see **Figure 11.25**). This pattern results from increasing dispersion forces as molecular weight increases. At ordinary temperatures and pressures, normal alkanes with 1 to 4 carbon atoms are gases, those with 5 to 20 carbon atoms are liquids, and those with more than 20 carbon atoms are waxy solids (see **Figure 11.26**).

homologous series Compounds of the same functional class that differ by a $—CH_2—$ group.

Because they are nonpolar, alkanes and other hydrocarbons are insoluble in water, which is a highly polar solvent. They are also less dense than water and thus float on it.

These two properties of hydrocarbons are partly responsible for the well-known serious effects of oil spills from ships (see **Figure 11.27**).

TABLE 11.8 Physical Properties of Some Normal Alkanes

Number of Carbon Atoms	IUPAC Name	Condensed Structural Formula	Melting Point (°C)	Boiling Point (°C)	Density (g/mL)
1	methane	CH_4	−182.5	−164.0	0.55
2	ethane	CH_3CH_3	−183.2	−88.6	0.57
3	propane	$CH_3CH_2CH_3$	−189.7	−42.1	0.58
4	butane	$CH_3CH_2CH_2CH_3$	−133.4	−0.5	0.60
5	pentane	$CH_3CH_2CH_2CH_2CH_3$	−129.7	36.1	0.63
6	hexane	$CH_3CH_2CH_2CH_2CH_2CH_3$	−95.3	68.9	0.66
7	heptane	$CH_3CH_2CH_2CH_2CH_2CH_2CH_3$	−90.6	98.4	0.68
8	octane	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	−56.8	125.7	0.70
9	nonane	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	−53.5	150.8	0.72
10	decane	$CH_3CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3$	−29.7	174.1	0.73

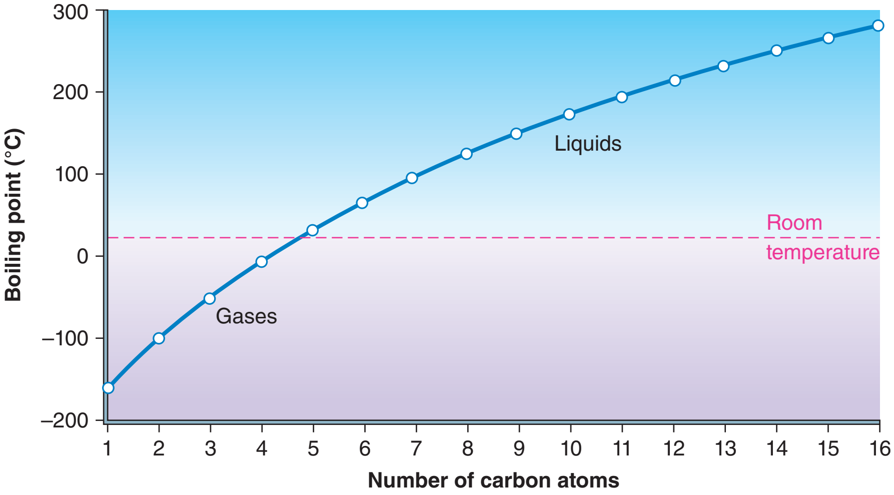


FIGURE 11.25 Normal alkane boiling points depend on chain length.

PublicDomainPictures/17907/Pixabay

FIGURE 11.26 In plants, solid long-chain alkanes are found in the waxy coatings of some species, protecting against water loss and harmful insects.

iStock.com/ufokim

FIGURE 11.27 Oil spills can have serious and long-lasting effects on the environment because of the insolubility of hydrocarbons in water.

ENVIRONMENTAL CONNECTIONS **11.1**

Reducing Your Carbon Footprint

Before something can be reduced, it must be defined. Your carbon footprint is defined as the total amount of greenhouse gases produced each year as a direct or indirect result of your activity. The value will be defined in terms of tons of carbon dioxide, CO_2, produced by your activities each year.

Some of your activities produce CO_2 directly. Examples of this include driving an automobile or heating your house by burning natural gas in a furnace. Other activities produce CO_2 indirectly. An example of this is when you purchase food or other produced goods in which CO_2 was released during their production.

The most common ways to reduce your CO_2 footprint can be summarized by the four *R's*: *Reduce*, *Reuse*, *Recycle*, and *Refuse*. For example, you can reduce your personal energy use by such things as turning off lights, unplugging electronics and appliances when they are not in use, and reducing the use of air conditioners in the summer and heating furnaces in the winter. An adjustment of just a degree or two in home temperature can make a significant difference in your personal carbon footprint. You can also switch to more efficient lightbulbs. LED bulbs use much less energy than incandescent bulbs.

The second R, Reuse, is demonstrated by people who take their own empty paper or cloth grocery bags with them when they go shopping. Another example of Reuse is the collection and reuse of lumber from a building demolition site.

Recycle, the third R, is catching on more and more in communities. Some communities provide special, recognizable, waste containers for recyclables that are picked up separately from regular refuse containers. Other communities have central locations with large bins for recyclables.

The fourth R, Refuse, is very personal. It requires a personal decision to act or refuse to act in specific ways. For example, you could refuse to drive your car for trips of less than a mile. You could ride a bicycle or walk instead. You could decide to fly less and drive your car instead.

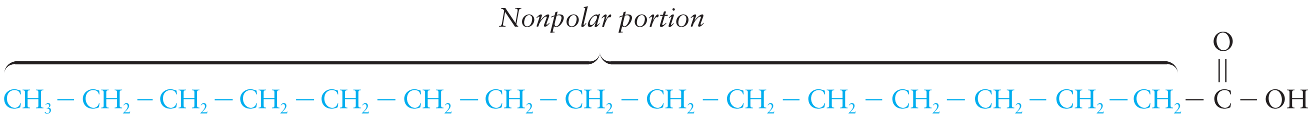
martiapunts/Shutterstock.com

LED bulbs use less energy than regular incandescent bulbs.

Liquid alkanes of higher molecular weight behave as *emollients* (skin softeners) when applied to the skin. An alkane mixture known as mineral oil is sometimes used to replace natural skin oils washed away by frequent bathing or swimming. Petroleum jelly (Vaseline is a well-known brand name) is a semisolid mixture of alkanes that is used as both an emollient and a protective film. Water and water solutions such as urine don't dissolve or penetrate the film, and the underlying skin is protected. Many cases of diaper rash have been prevented or treated this way.

The word **hydrophobic** (literally "water fearing") is often used to refer to molecules or parts of molecules that are insoluble in water. Many biomolecules, the large organic molecules associated with living organisms, contain nonpolar (hydrophobic) parts. Thus, such molecules are not water-soluble. Palmitic acid, for example, contains a large nonpolar hydrophobic portion and is insoluble in water.

hydrophobic Molecules or parts of molecules that repel (are insoluble in) water.



$$\overbrace{CH_3-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2}^{\textit{Nonpolar portion}}-\overset{\overset{\displaystyle O}{\|}}{C}-OH$$

palmitic acid

11.11 Alkane Reactions

Learning Objective 12 Write alkane combustion reactions.

The alkanes are the least reactive of all organic compounds. In general, they do not react with strong acids (such as sulfuric acid), strong bases (such as sodium hydroxide), most oxidizing agents (such as potassium dichromate), or most reducing agents (such as sodium metal).

This unreactive nature is reflected in the name *paraffins*, sometimes used to identify alkanes (from Latin words that mean "little affinity"). Paraffin wax, sometimes used to seal jars of homemade preserves, is a mixture of solid alkanes. Paraffin wax is also used in the preparation of milk cartons and wax paper. The inertness of the compounds in the wax makes it ideal for these uses. Alkanes do undergo reactions with halogens such as chlorine and bromine, but these are not important for our purposes.

Perhaps the most significant reaction of alkanes is the rapid oxidation called combustion. In the presence of ample oxygen, alkanes burn to form carbon dioxide and water, liberating large quantities of heat:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O + 212.8\text{ kcal/mol} \qquad (11.4)$$

It is this type of reaction that accounts for the wide use of hydrocarbons as fuels.

Natural gas contains methane (80–95%), some ethane, and small amounts of other hydrocarbons. Propane and butane are extracted from natural gas and sold in pressurized metal containers (bottled gas). In this form, they are used for heating and cooking in campers, trailers, boats, and rural homes.

Gasoline is a mixture of hydrocarbons (primarily alkanes) that contain 5 to 12 carbon atoms per molecule. Diesel fuel is a similar mixture, except the molecules contain 12 to 16 carbon atoms. The hot CO_2 and water vapor generated during combustion in an internal combustion engine have a much greater volume than the air and fuel mixture. It is this sudden increase in gaseous volume and pressure that pushes the pistons and delivers power to the crankshaft.

If there is not enough oxygen available, incomplete combustion of hydrocarbons occurs, and some carbon monoxide (CO) or even carbon may be produced (see **Reactions 11.5** and **11.6**):

$$2CH_4 + 3O_2 \rightarrow 2CO + 4H_2O \qquad (11.5)$$

$$CH_4 + O_2 \rightarrow C + 2H_2O \qquad (11.6)$$

These reactions are usually undesirable because CO is toxic (see **Figure 11.28**), and carbon deposits hinder engine performance. Occasionally, however, incomplete combustion is deliberately caused; specific carbon blacks (particularly lampblack, a pigment for ink) are produced by the incomplete combustion of natural gas.

CARBON
MONOXIDE
ALARM

Daniela White Images/Moment/
Getty Images

FIGURE 11.28 Carbon monoxide detectors are available for homes with fuel-burning furnaces and appliances.

Example 11.11 Writing Combustion Reactions

The production of carbon monoxide through incomplete combustion can result in dull headaches, nausea, confusion and loss of consciousness. Write a balanced equation for the following combustion reactions.

a. Pentane + $O_2 \rightarrow CO_2 + H_2O$
b. Cyclohexane + $O_2 \rightarrow CO + H_2O$

Solution a.

STEP 1: Write the molecular formula for pentane using the formula C_nH_{2n+2}, where $n = 5$; the number of hydrogens would be 12. The formula for pentane is C_5H_{12}.

$$C_5H_{12} + O_2 \rightarrow CO_2 + H_2O$$

STEP 2: Since the element oxygen is the simplest, let's leave it last and start with carbon by placing the coefficient 5 in front of CO_2.

$$C_5H_{12} + O_2 \rightarrow 5CO_2 + H_2O$$

STEP 3: Next, balance the hydrogen by placing a 6 in front of H_2O.

$$C_5H_{12} + O_2 \rightarrow 5CO_2 + 6H_2O$$

STEP 4: Adding the oxygen atoms on the right side gives

$$6 \times 1 = 6 \text{ plus } 5 \times 2 = 10 \quad \text{Total} = 16$$

STEP 5: To get 16 oxygen atoms on the left, place a coefficient 8 in front of the O_2. The equation is now correctly balanced.

$$C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O$$

Solution b.

STEP 1: Convert cyclohexane to a molecular formula. Looking at the structure in **Table 11.7**, we see 6 carbon atoms and 12 hydrogen atoms, two fewer than in an open-chain alkane.

$$C_6H_{12} + O_2 \rightarrow CO + H_2O$$

STEP 2: Starting with C, place a coefficient 6 in front of CO to give

$$C_6H_{12} + O_2 \rightarrow 6CO + H_2O$$

STEP 3: With 12 hydrogen atoms on the left, place a coefficient 6 in front of H_2O.

$$C_6H_{12} + O_2 \rightarrow 6CO + 6H_2O$$

STEP 4: The total number of oxygen atoms on the right is 6 + 6 or 12.

STEP 5: Place a coefficient 6 in front of O_2 to give 12 oxygen atoms on the left, and the equation is correctly balanced.

$$C_6H_{12} + 6O_2 \rightarrow 6CO + 6H_2O$$

✔ **LEARNING CHECK 11.4** Write a balanced equation for the following combustion reactions:

a. The incomplete combustion of pentane, giving CO and H_2O as products.
b. The complete combustion of hexane, giving CO_2 and H_2O as products.

Environmental Career Description

APIARIST (BEEKEEPER)

According to a NASA research and information website, "Bees are important because they pollinate approximately 130 agricultural crops in the US including fruit, fiber, nut, and vegetable crops. Bee pollination adds approximately 14 billion dollars annually to improve crop yield and quality." Although honeybees are not native to the United States, Americans depend on them not only for honey, but also for much of our food supply.

Apiarists, also known as beekeepers, manage and maintain colonies of bees for the purpose of collecting honey and other bee products such as royal jelly, beeswax, and propolis for the manufacture of a variety of products, but also to provide pollination services for agriculture. Beekeepers may keep one, or a few hives as a hobby, or work as part of a large commercial venture.

A college degree is not necessary for this career, but many apiarists hold degrees in the biological sciences. Knowledge of chemistry is especially useful in understanding what pesticides are harmful to bees, what mixtures of syrups and supplements are useful for over-wintering the bees and in developing products from the hive for sale. Knowledge of biology is invaluable, since apiarists are working with living organisms and ecosystems. Universities such as Cornell, Texas A&M, and Florida State maintain bee research programs supporting graduate-level research in the field of honeybee research. They also host community education for hobbyists to advanced beekeepers.

According to *Bee Keeping Career Profile and Job Outlook*, "A beekeeper is responsible for assessing the health of the hive, checking for mite infestations, monitoring and treating the hive when health problems arise, and maintaining detailed records of health, medication administration, and honey production."

A beekeeper may also be responsible for preparing bees and equipment for pollination activities, feeding bees, cleaning and constructing hives, raising and replacing queen bees, dividing colonies when necessary, and replacing combs. Some beekeepers may work directly with honey-processing and bottling equipment.

Beekeepers must work long hours during the warmer months, spending most of their time outdoors in variable weather conditions. Work may be required on nights, weekends, and holidays. Beekeepers must wear special protective clothing such as veils, gloves, and suits. They also must properly use bee smokers and other hive tools to safely access the hive."

Beekeeping career options vary widely depending on education and personal interests. Travel opportunities exist for apiarists in large international commercial companies. Beekeeping is a widely varied, essential career, with global possibilities.

Concept Summary

11.1 Carbon: The Element of Organic Compounds

Learning Objective: Do you understand the general importance of organic chemical compounds? Can you recognize the molecular formulas of organic and inorganic compounds?

- Organic compounds contain carbon.
- Organic chemistry is the study of those compounds.
- Inorganic chemistry is the study of the elements and all noncarbon compounds.
- Carbon compounds are of tremendous everyday importance to life on the Earth.
- They are the basis of all life processes.

11.2 Organic and Inorganic Compounds Compared

Learning Objective: Can you explain some general differences between inorganic and organic compounds?

- The properties of organic and inorganic compounds often differ, largely as a result of bonding differences.
- Organic compounds contain primarily covalent bonds, whereas ionic bonding is more prevalent in inorganic compounds.

11.3 Bonding Characteristics and Isomerism

Learning Objective: Can you use structural formulas to identify compounds that are isomers of each other?

- Large numbers of organic compounds are possible because carbon atoms link to form chains and networks.
- An additional reason for the existence of so many organic compounds is the phenomenon of isomerism.
- Isomers are compounds that have the same molecular formula but different arrangements of atoms.

11.4 Functional Groups: The Organization of Organic Chemistry

Learning Objective: Can you write condensed or expanded structural formulas for compounds?

- All organic compounds are grouped into classes based on characteristic features called functional groups.
- Compounds with their functional groups are represented by two types of structural formulas.
- Expanded structural formulas show all covalent bonds.
- Condensed structural formulas show no covalent bonds or only selected bonds.

11.5 Alkane Structures

Learning Objective: Can you classify alkanes as normal or branched?

- Alkanes are hydrocarbons that contain only single covalent bonds and can be represented by the formula C_nH_{2n+2}.
- Alkanes possess a three-dimensional geometry in which each carbon is surrounded by four bonds directed to the corners of a tetrahedron.
- Methane, the simplest alkane, is an important fuel (natural gas) and a chemical feedstock for the preparation of other organic compounds.
- The number of structural isomers possible for an alkane increases dramatically with the number of carbon atoms present in the molecule.
- The straight-chain isomer is called a normal alkane.
- Others are called branched isomers.

11.6 Conformations of Alkanes

Learning Objective: Can you use structural formulas to determine whether compounds are structural isomers?

- Rotation about the single bonds between carbon atoms allows alkanes to exist in many different conformations.
- When an alkane is drawn using only two dimensions, the structure can be represented in a variety of ways, as long as the order of bonding is not changed.

11.7 Alkane Nomenclature

Learning Objective: Can you assign IUPAC names and draw structural formulas for alkanes?

- Some simple alkanes are known by common names.
- More complex compounds are usually named using the IUPAC system.
- The characteristic IUPAC ending for alkanes is *-ane*.

11.8 Cycloalkanes

Learning Objective: Can you assign IUPAC names and draw structural formulas for cycloalkanes?

- These are alkanes in which the carbon atoms form a ring.
- The prefix *cyclo-* is used in the names of these compounds to indicate their cyclic nature.

11.9 The Shape of Cycloalkanes

Learning Objective: Can you name and draw structural formulas for *cis-trans* isomers of cycloalkanes?

- The carbon atom rings of cycloalkanes are usually shown as planar, although only cyclopropane is planar.
- Because rotation about the single bonds in the ring is restricted, certain disubstituted cycloalkanes can exist as *cis-trans* isomers.

11.10 Physical Properties of Alkanes

Learning Objective: Can you describe the key physical properties of alkanes?

- The physical properties of alkanes are typical of all hydrocarbons:
    - nonpolar
    - insoluble in water
    - less dense than water
    - increasing melting and boiling points with increasing molecular weight.

11.11 Alkane Reactions

Learning Objective: Can you write alkane combustion reactions?

- Alkanes are relatively unreactive and remain unchanged by most reagents.
- The reaction that is most significant is combustion.

Key Terms and Concepts

Alkane (11.5)
Alkyl group (11.7)
Branched alkane (11.5)
cis- (11.9)
Condensed structural formula (11.4)
Conformations (11.6)
Cycloalkane (11.8)
Expanded structural formula (11.4)
Functional group (11.4)
cis-trans isomers (11.9)
Homologous series (11.10)
Hybrid orbital (11.3)
Hydrocarbon (11.5)
Hydrophobic (11.10)
Inorganic chemistry (11.1)
Isomerism (11.3)
Normal alkane (11.5)
Organic chemistry (11.1)
Organic compound (11.1)
Saturated hydrocarbon (11.5)
Stereoisomers (11.9)
Structural isomers (11.3)
trans- (11.9)

Key Equations

1. Complete combustion of alkanes (**Section 11.11**):	Alkane + $O_2 \rightarrow CO_2 + H_2O$
2. Incomplete combustion of alkanes (**Section 11.11**):	Alkane + $O_2 \rightarrow$ CO (or C) + H_2O

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Carbon: The Element of Organic Compounds (Section 11.1)

11.1 Why were the compounds of carbon originally called organic compounds?

11.2 Name at least six items you recognize to be composed of organic compounds.

11.3 Describe what Wöhler did that made the vital force theory highly questionable.

11.4 What is the unique structural feature shared by all organic compounds?

11.5 Classify each of the following compounds as organic or inorganic:

a. KBr
b. H_2O
c. H—C≡C—H
d. LiOH

Organic and Inorganic Compounds Compared (Section 11.2)

11.6 Classify each of the following compounds as organic or inorganic.

a. NH_3
b. CH_3—NH_2
c. NH_4NCO
d. CO_2

11.7 What kind of bond between atoms is most prevalent among organic compounds?

11.8 Are the majority of all compounds that are insoluble in water organic or inorganic? Why?

11.9 Indicate for each of the following characteristics whether it more likely describes an inorganic or an organic compound. Give one reason for your answer.

a. This compound is a liquid that readily burns.
b. A white solid upon heating is found to melt at 735°C.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

c. A liquid added to water floats on the surface and does not dissolve.

d. This compound exists as a gas at room temperature and ignites easily.

11.10 Indicate for each of the following characteristics whether it more likely describes an inorganic or organic compound. Give one reason for each of your answers.

a. A solid substance melts at 65°C.

b. This compound is soluble in water and does not burn.

c. A water solution of this substance conducts electricity.

d. A green solid resists melting when heated to 600°C.

11.11 Devise a test, based on the general properties in **Table 11.1**, that you could use to quickly distinguish between the substances in each of the following pairs:

a. Gasoline (liquid, organic) and water (liquid, inorganic)

b. Naphthalene (solid, organic) and sodium chloride (solid, inorganic)

c. Methane (gaseous, organic) and hydrogen chloride (gaseous, inorganic)

11.12* Explain why organic compounds are nonconductors of electricity.

11.13 Explain why the rate of chemical reactions is generally slow for organic compounds and usually fast for inorganic compounds.

Bonding Characteristics and Isomerism (Section 11.3)

11.14 Give two reasons for the existence of the tremendous number of organic compounds.

11.15* How many of carbon's electrons are unpaired and available for bonding according to an sp^3 hybridization model?

11.16* Describe what atomic orbitals overlap to produce a carbon–hydrogen bond in CH_4.

11.17 What molecular geometry exists when a central carbon atom bonds to four other atoms?

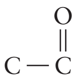
11.18* Compare the shapes of unhybridized p and hybridized sp^3 orbitals.

11.19 Use Example 11.1 and **Tables 11.2** and **11.6** to determine the number of covalent bonds formed by atoms of the following elements: carbon, hydrogen, oxygen, nitrogen, and bromine.

11.20 Complete the following structures by adding hydrogen atoms where needed:

a. $\mathrm{C-C-C}$

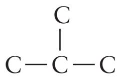
b. $\mathrm{C-C=C}$

c.


$$\mathrm{C-\overset{\displaystyle O}{\overset{\|}{C}}}$$

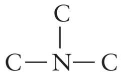
d. $\mathrm{C-C-N}$

11.21 Complete the following structures by adding hydrogen atoms where needed.

a.


$$\mathrm{C-\overset{\displaystyle C}{\overset{|}{C}}-C}$$

c. $\mathrm{C-C\equiv C-C}$

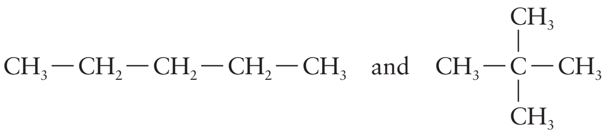
b.


$$\mathrm{C-\overset{\displaystyle C}{\overset{|}{N}}-C}$$

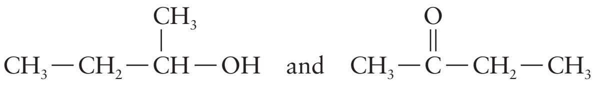
d. $\mathrm{C-O-C}$

11.22 Which of the following pairs of compounds are structural isomers?

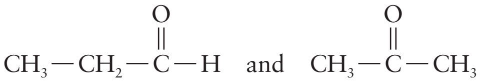
a. $\mathrm{CH_3-CH=CH-CH_3}$ and $\mathrm{CH_3-CH_2-CH_2-CH_3}$

b.


$$\mathrm{CH_3-CH_2-CH_2-CH_2-CH_3 \quad and \quad CH_3-\overset{\displaystyle CH_3}{\overset{|}{\underset{\underset{\displaystyle CH_3}{|}}{C}}}-CH_3}$$

c.


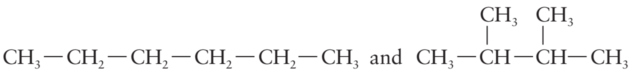
$$\mathrm{CH_3-CH_2-\overset{\displaystyle CH_3}{\overset{|}{CH}}-OH \quad and \quad CH_3-\overset{\displaystyle O}{\overset{\|}{C}}-CH_2-CH_3}$$

d.


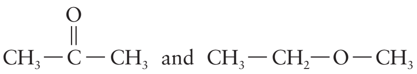
$$\mathrm{CH_3-CH_2-\overset{\displaystyle O}{\overset{\|}{C}}-H \quad and \quad CH_3-\overset{\displaystyle O}{\overset{\|}{C}}-CH_3}$$

11.23 Which of the following pairs of compounds are structural isomers?

a. $\mathrm{CH_3\_CH_2\_CH_2\_NH_2}$ and $\mathrm{CJ_3\_CH_2\_NH\_CH_3}$

b.


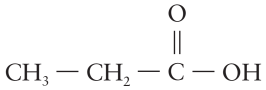
$$\mathrm{CH_3-CH_2-CH_2-CH_2-CH_2-CH_3 \quad and \quad CH_3-\overset{\displaystyle CH_3}{\overset{|}{CH}}-\overset{\displaystyle CH_3}{\overset{|}{CH}}-CH_3}$$

c.


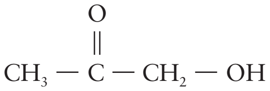
$$\mathrm{CH_3-\overset{\displaystyle O}{\overset{\|}{C}}-CH_3 \quad and \quad CH_3-CH_2-O-CH_3}$$

d. $\mathrm{CH_3-CH_2-CH=CH_2}$ and $\mathrm{CH_3-C\equiv C-CH_3}$

11.24 Group all the following compounds together that represent structural isomers of each other:

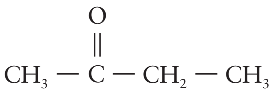
a.


$$\mathrm{CH_3-CH_2-\overset{\displaystyle O}{\overset{\|}{C}}-OH}$$

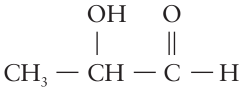
b.


$$\mathrm{CH_3-\overset{\displaystyle O}{\overset{\|}{C}}-CH_2-OH}$$

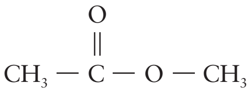
c. $\mathrm{CH_3-CH_2-CH_2-OH}$

d.


$$\mathrm{CH_3-\overset{\displaystyle O}{\overset{\|}{C}}-CH_2-CH_3}$$

e.


$$\mathrm{CH_3-\overset{\displaystyle OH}{\overset{|}{CH}}-\overset{\displaystyle O}{\overset{\|}{C}}-H}$$

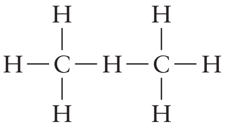
f.


$$\mathrm{CH_3-\overset{\displaystyle O}{\overset{\|}{C}}-O-CH_3}$$

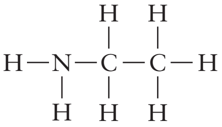
g. $\mathrm{HO-CH_2-CH_2-CH_2-OH}$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

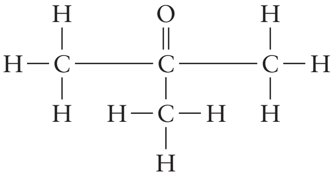
11.25 On the basis of the number of covalent bonds possible for each atom, determine which of the following structural formulas are correct. Explain what is wrong with the incorrect structures.

a. 

$$\mathrm{H{-}\overset{H}{\underset{H}{C}}{-}H{-}\overset{H}{\underset{H}{C}}{-}H}$$

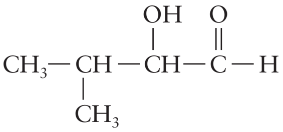
b. 

$$\mathrm{H{-}\underset{H}{N}{-}\overset{H}{\underset{H}{C}}{-}\overset{H}{\underset{H}{C}}{-}H}$$

c. 

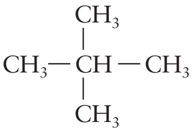
d. $\mathrm{CH_3{-}C{=}C{-}CH_3}$

11.26 On the basis of the number of covalent bonds possible for each atom, determine which of the following structural formulas are correct. Explain what is wrong with the incorrect structures.

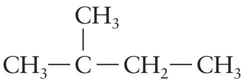
a. 

$$\mathrm{CH_3{-}\underset{CH_3}{CH}{-}\overset{OH}{CH}{-}\overset{O}{\overset{\|}{C}}{-}H}$$

c. $\mathrm{CH_3{-}O{-}CH_2{-}CH_4}$

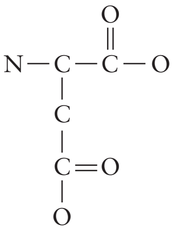
b. 

$$\mathrm{CH_3{-}\overset{CH_3}{\underset{CH_3}{CH}}{-}CH_3}$$

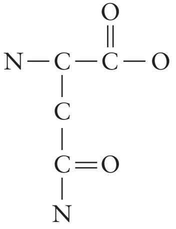
d. 

$$\mathrm{CH_3{-}\overset{CH_3}{C}{-}CH_2{-}CH_3}$$

11.27 Aspartic acid is an essential component of proteins. It has the basic structure shown here. Complete the structure by adding hydrogen atoms on the basis of the number of covalent bonds possible for each atom.



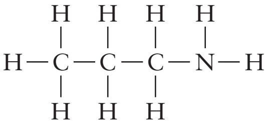
11.28 Asparagine is an essential component of proteins. It has the basic structure shown here. Complete the structure by adding hydrogen atoms on the basis of the number of covalent bonds possible for each atom.



Functional Groups: The Organization of Organic Chemistry (Section 11.4)

11.29 Identify each of the following as a condensed structural formula, expanded structural formula, or molecular formula:

a. $\mathrm{CH_3CH_2CH_2{-}NH_2}$

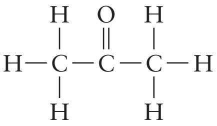
b. 

$$\mathrm{H{-}\overset{H}{\underset{H}{C}}{-}\overset{H}{\underset{H}{C}}{-}\overset{H}{\underset{H}{C}}{-}\overset{H}{N}{-}H}$$

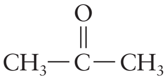
c. $\mathrm{CH_3{-}CH_2{-}CH_2{-}NH_2}$

d. $\mathrm{C_3H_9N}$

11.30 Identify each of the following as a condensed structural formula, expanded structural formula, or molecular formula:

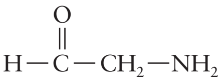
a. 

$$\mathrm{H{-}\overset{H}{\underset{H}{C}}{-}\overset{O}{\overset{\|}{C}}{-}\overset{H}{\underset{H}{C}}{-}H}$$

b. 

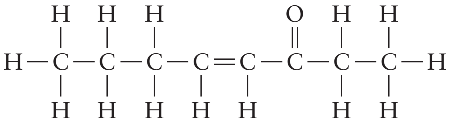
$$\mathrm{CH_3{-}\overset{O}{\overset{\|}{C}}{-}CH_3}$$

c. $\mathrm{C_3H_6O}$

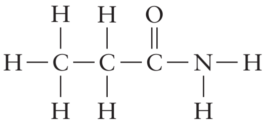
d. 

$$\mathrm{H{-}\overset{O}{\overset{\|}{C}}{-}CH_2{-}NH_2}$$

11.31 Write a condensed structural formula for the following compounds:

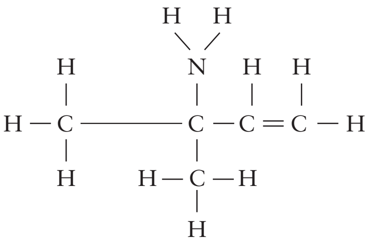
a. 

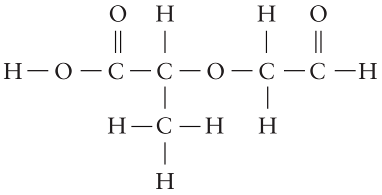
$$\mathrm{H{-}\overset{H}{\underset{H}{C}}{-}\overset{H}{\underset{H}{C}}{-}\overset{H}{\underset{H}{C}}{-}\underset{H}{C}{=}\underset{H}{C}{-}\overset{O}{\overset{\|}{C}}{-}\overset{H}{\underset{H}{C}}{-}\overset{H}{\underset{H}{C}}{-}H}$$

b. 

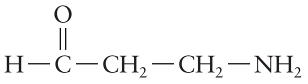
$$\mathrm{H{-}\overset{H}{\underset{H}{C}}{-}\overset{H}{\underset{H}{C}}{-}\overset{O}{\overset{\|}{C}}{-}\underset{H}{N}{-}H}$$

11.32 Write a condensed structural formula for the following compounds:

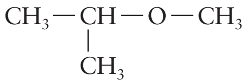
a. 

b. 

11.33* Write an expanded structural formula for the following:

a. 

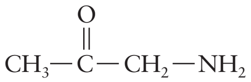
$$H-\overset{\displaystyle O}{\overset{\|}{C}}-CH_2-CH_2-NH_2$$

b. 

$$CH_3-\underset{\displaystyle CH_3}{\underset{|}{CH}}-O-CH_3$$

11.34 Write an expanded structural formula for the following:

a. $CH_3-CH_2-O-CH_2-O-CH_3$

b. 

$$CH_3-\overset{\displaystyle O}{\overset{\|}{C}}-CH_2-NH_2$$

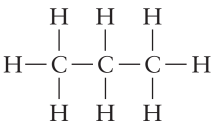
Alkane Structures (Section 11.5)

11.35 The name of the normal alkane containing 10 carbon atoms is decane. What are the molecular and condensed structural formulas for decane?

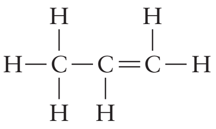
11.36 The name of the normal alkane containing 12 carbon atoms is dodecane. What are the molecular and condensed structural formulas for dodecane?

11.37 What is the difference between an unsaturated hydrocarbon and a saturated hydrocarbon?

11.38 Classify each of the following hydrocarbons as saturated or unsaturated:

a. 

$$\begin{array}{ccccccccc} & & H & & H & & H & & \\ & & | & & | & & | & & \\ H & - & C & - & C & - & C & - & H \\ & & | & & | & & | & & \\ & & H & & H & & H & & \end{array}$$

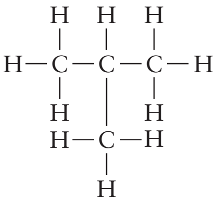
b. 

$$\begin{array}{ccccccccc} & & H & & & & H & & \\ & & | & & & & | & & \\ H & - & C & - & C & = & C & - & H \\ & & | & & | & & & & \\ & & H & & H & & & & \end{array}$$

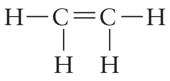
c. $CH_3-C\equiv C-CH_3$

d. $CH_3-CH_2-CH_2=CH_3$

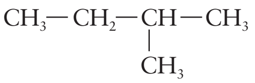
11.39 Classify each of the following hydrocarbons as saturated or unsaturated:

a. 

$$\begin{array}{ccccccccc} & & H & & H & & H & & \\ & & | & & | & & | & & \\ H & - & C & - & C & - & C & - & H \\ & & | & & | & & | & & \\ & & H & & | & & H & & \\ & & H & - & C & - & H & & \\ & & & & | & & & & \\ & & & & H & & & & \end{array}$$

b. 

$$\begin{array}{ccccccc} H & - & C & = & C & - & H \\ & & | & & | & & \\ & & H & & H & & \end{array}$$

c. 

$$CH_3-CH_2-\underset{\displaystyle CH_3}{\underset{|}{CH}}-CH_3$$

d. $CH_3-CH_2-CH=CH_2$

11.40 Using the general formula for an alkane, calculate the following:

a. The number of hydrogen atoms present in heptane.

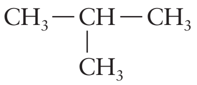
b. The number of carbon atoms present in an alkane with 22 hydrogen atoms.

11.41 Using the general formula for an alkane, calculate the following:

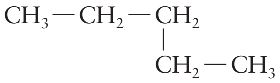
a. The number of hydrogen atoms present in octane.

b. The number of carbon atoms present in an alkane with 28 hydrogen atoms.

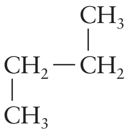
11.42 Classify each of the following compounds as a normal alkane or a branched alkane:

a. 

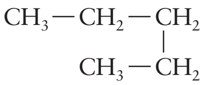
$$CH_3-\underset{\displaystyle CH_3}{\underset{|}{CH}}-CH_3$$

b. 

$$\begin{array}{lllll} CH_3 & - & CH_2 & - & CH_2 \\ & & & & | \\ & & & & CH_2-CH_3 \end{array}$$

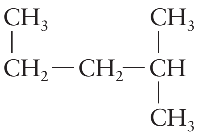
c. 

$$\begin{array}{lll} & & CH_3 \\ & & | \\ CH_2 & - & CH_2 \\ | & & \\ CH_3 & & \end{array}$$

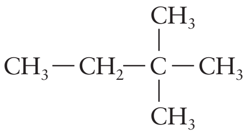
d. 

$$\begin{array}{lllll} CH_3 & - & CH_2 & - & CH_2 \\ & & & & | \\ & & CH_3 & - & CH_2 \end{array}$$

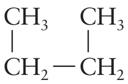
11.43 Classify each of the following compounds as a normal alkane or a branched alkane:

a. 

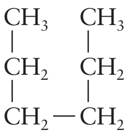
$$\begin{array}{lllll} CH_3 & & & & CH_3 \\ | & & & & | \\ CH_2 & - & CH_2 & - & CH \\ & & & & | \\ & & & & CH_3 \end{array}$$

b. 

$$CH_3-CH_2-\overset{\displaystyle CH_3}{\overset{|}{\underset{\displaystyle CH_3}{\underset{|}{C}}}}-CH_3$$

c. 

$$\begin{array}{lll} CH_3 & & CH_3 \\ | & & | \\ CH_2 & - & CH_2 \end{array}$$

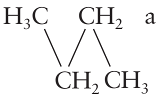
d. 

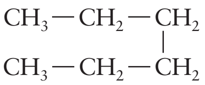
$$\begin{array}{lll} CH_3 & & CH_3 \\ | & & | \\ CH_2 & & CH_2 \\ | & & | \\ CH_2 & - & CH_2 \end{array}$$

Conformations of Alkanes (Section 11.6)

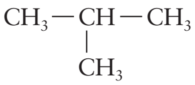
11.44 Why are different conformations of an alkane not considered structural isomers?

11.45* Which of the following pairs represent structural isomers, and which are simply the same compound?

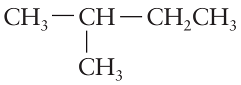
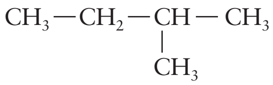
a.  and $CH_3CH_2CH_2CH_3$

b. 

$\begin{array}{ccccc} CH_3 & - & CH_2 & - & CH_2 \\ & & & & | \\ CH_3 & - & CH_2 & - & CH_2 \end{array}$ and $CH_3CH_2CH_2CH_2CH_2CH_3$

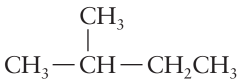
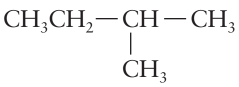
c. 

$\begin{array}{ccccc} CH_3 & - & CH & - & CH_3 \\ & & | & & \\ & & CH_3 & & \end{array}$ and $CH_3CH_2CH_2CH_3$

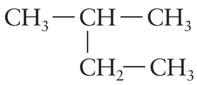
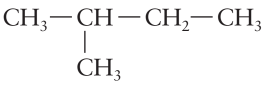
d.  and 

$\begin{array}{ccccc} CH_3 & - & CH & - & CH_2CH_3 \\ & & | & & \\ & & CH_3 & & \end{array}$ and $\begin{array}{ccccccc} CH_3 & - & CH_2 & - & CH & - & CH_3 \\ & & & & | & & \\ & & & & CH_3 & & \end{array}$

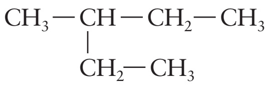
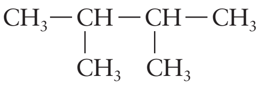
11.46 Which of the following pairs represents structural isomers, and which are simply the same compound?

a.  and 

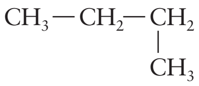
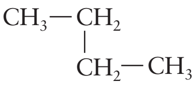
$\begin{array}{ccccc} & & CH_3 & & \\ & & | & & \\ CH_3 & - & CH & - & CH_2CH_3 \end{array}$ and $\begin{array}{ccccc} CH_3CH_2 & - & CH & - & CH_3 \\ & & | & & \\ & & CH_3 & & \end{array}$

b.  and 

$\begin{array}{ccccc} CH_3 & - & CH & - & CH_3 \\ & & | & & \\ & & CH_2-CH_3 & & \end{array}$ and $\begin{array}{ccccccc} CH_3 & - & CH & - & CH_2 & - & CH_3 \\ & & | & & & & \\ & & CH_3 & & & & \end{array}$

c.  and 

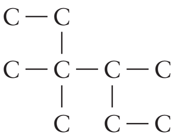
$\begin{array}{ccccccc} CH_3 & - & CH & - & CH_2 & - & CH_3 \\ & & | & & & & \\ & & CH_2-CH_3 & & & & \end{array}$ and $\begin{array}{ccccccc} CH_3 & - & CH & - & CH & - & CH_3 \\ & & | & & | & & \\ & & CH_3 & & CH_3 & & \end{array}$

d.  and 

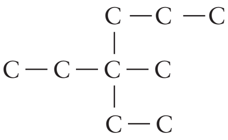
$\begin{array}{ccccc} CH_3 & - & CH_2 & - & CH_2 \\ & & & & | \\ & & & & CH_3 \end{array}$ and $\begin{array}{ccc} CH_3 & - & CH_2 \\ & & | \\ & & CH_2-CH_3 \end{array}$

Alkane Nomenclature (Section 11.7)

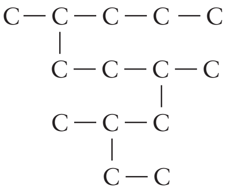
11.47 For each of the following carbon skeletons, give the number of carbon atoms in the longest continuous chain:

a. 

$\begin{array}{ccccccc} C & - & C & & & & \\ & & | & & & & \\ C & - & C & - & C & - & C \\ & & | & & | & & \\ & & C & & C & - & C \end{array}$

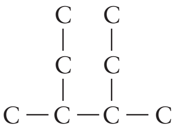
c. 

$\begin{array}{ccccccccc} & & & & C & - & C & - & C \\ & & & & | & & & & \\ C & - & C & - & C & - & C & & \\ & & & & | & & & & \\ & & & & C & - & C & & \end{array}$

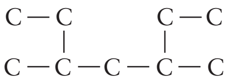
b. 

$\begin{array}{ccccccccc} C & - & C & - & C & - & C & - & C \\ & & | & & & & & & \\ & & C & - & C & - & C & - & C \\ & & & & & & | & & \\ & & C & - & C & - & C & & \\ & & & & | & & & & \\ & & & & C & - & C & & \end{array}$

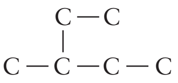
11.48 For each of the following carbon skeletons, give the number of carbon atoms in the longest continuous chain:

a. 

$\begin{array}{ccccccc} & & C & & C & & \\ & & | & & | & & \\ & & C & & C & & \\ & & | & & | & & \\ C & - & C & - & C & - & C \end{array}$

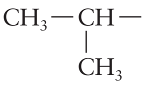
c. 

$\begin{array}{ccccccccc} C & - & C & & & & C & - & C \\ & & | & & & & | & & \\ C & - & C & - & C & - & C & - & C \end{array}$

b. 

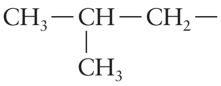
$\begin{array}{ccccccc} & & C & - & C & & \\ & & | & & & & \\ C & - & C & - & C & - & C \end{array}$

11.49 Identify the following alkyl groups:

a. 

$\begin{array}{cccc} CH_3 & - & CH & - \\ & & | & \\ & & CH_3 & \end{array}$

b. $CH_3-CH_2-CH_2-CH_2-$

c. 

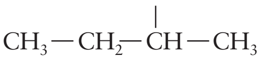
$\begin{array}{cccccc} CH_3 & - & CH & - & CH_2 & - \\ & & | & & & \\ & & CH_3 & & & \end{array}$

d. CH_3-

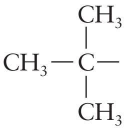
11.50 Identify the following alkyl groups.

a. $CH_3-CH_2-CH_2-$

b. CH_3-CH_2-

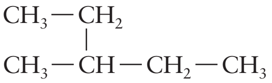
c. 

$\begin{array}{ccccccc} & & & & | & & \\ CH_3 & - & CH_2 & - & CH & - & CH_3 \end{array}$

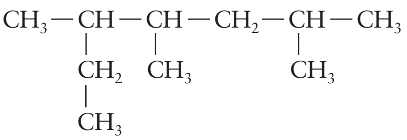
d. 

$\begin{array}{cccc} & & CH_3 & \\ & & | & \\ CH_3 & - & C & - \\ & & | & \\ & & CH_3 & \end{array}$

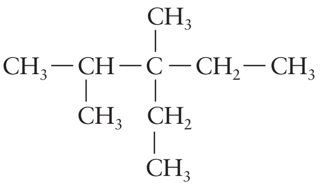
11.51 Give the correct IUPAC name for each of the following alkanes:

a. 

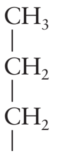
$\begin{array}{ccccccc} CH_3 & - & CH_2 & & & & \\ & & | & & & & \\ CH_3 & - & CH & - & CH_2 & - & CH_3 \end{array}$

b. 

$\begin{array}{ccccccccccc} CH_3 & - & CH & - & CH & - & CH_2 & - & CH & - & CH_3 \\ & & | & & | & & & & | & & \\ & & CH_2 & & CH_3 & & & & CH_3 & & \\ & & | & & & & & & & & \\ & & CH_3 & & & & & & & & \end{array}$

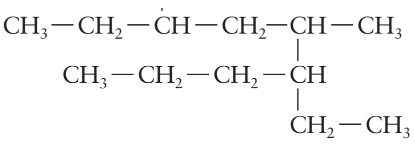
c. 

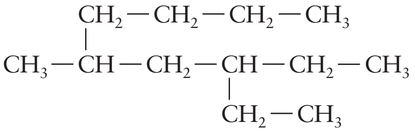
$\begin{array}{ccccccccc} & & & & CH_3 & & & & \\ & & & & | & & & & \\ CH_3 & - & CH & - & C & - & CH_2 & - & CH_3 \\ & & | & & | & & & & \\ & & CH_3 & & CH_2 & & & & \\ & & & & | & & & & \\ & & & & CH_3 & & & & \end{array}$



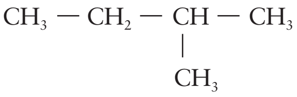
$\begin{array}{c} CH_3 \\ | \\ CH_2 \\ | \\ CH_2 \\ | \end{array}$

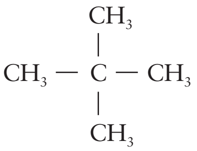
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

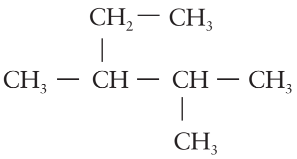
d. 
$$\begin{array}{ccccccccccc}
CH_3 & - & CH_2 & - & CH & - & CH_2 & - & CH & - & CH_3\\
 & & & & & & & & | & & \\
 & & CH_3 & - & CH_2 & - & CH_2 & - & CH & & \\
 & & & & & & & & | & & \\
 & & & & & & & & CH_2 & - & CH_3
\end{array}$$

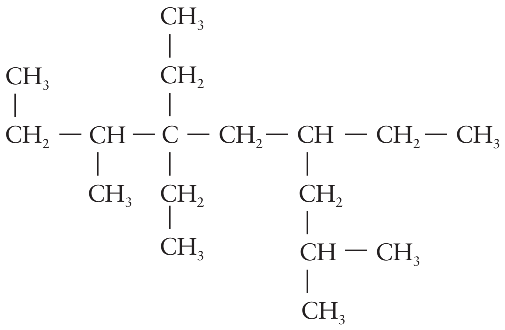
e. 
$$\begin{array}{ccccccccccc}
 & & CH_2 & - & CH_2 & - & CH_2 & - & CH_3 & & \\
 & & | & & & & & & & & \\
CH_3 & - & CH & - & CH_2 & - & CH & - & CH_2 & - & CH_3\\
 & & & & & & | & & & & \\
 & & & & & & CH_2 & - & CH_3 & &
\end{array}$$

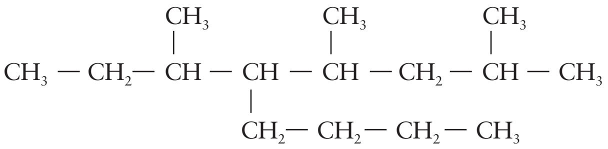
11.52 Give the correct IUPAC name for each of the following alkanes:

a. 
$$\begin{array}{ccccccc}
CH_3 & - & CH_2 & - & CH & - & CH_3\\
 & & & & | & & \\
 & & & & CH_3 & &
\end{array}$$

b. 
$$\begin{array}{ccccc}
 & & CH_3 & & \\
 & & | & & \\
CH_3 & - & C & - & CH_3\\
 & & | & & \\
 & & CH_3 & &
\end{array}$$

c. 
$$\begin{array}{ccccccc}
 & & CH_2 & - & CH_3 & & \\
 & & | & & & & \\
CH_3 & - & CH & - & CH & - & CH_3\\
 & & & & | & & \\
 & & & & CH_3 & &
\end{array}$$

d. 
$$\begin{array}{ccccccccccccc}
 & & & & CH_3 & & & & & & & & \\
 & & & & | & & & & & & & & \\
CH_3 & & & & CH_2 & & & & & & & & \\
| & & & & | & & & & & & & & \\
CH_2 & - & CH & - & C & - & CH_2 & - & CH & - & CH_2 & - & CH_3\\
 & & | & & | & & & & | & & & & \\
 & & CH_3 & & CH_2 & & & & CH_2 & & & & \\
 & & & & | & & & & | & & & & \\
 & & & & CH_3 & & & & CH & - & CH_3 & & \\
 & & & & & & & & | & & & & \\
 & & & & & & & & CH_3 & & & &
\end{array}$$

e. 
$$\begin{array}{ccccccccccccccc}
 & & & & CH_3 & & & & CH_3 & & & & CH_3 & & \\
 & & & & | & & & & | & & & & | & & \\
CH_3 & - & CH_2 & - & CH & - & CH & - & CH & - & CH_2 & - & CH & - & CH_3\\
 & & & & & & | & & & & & & & & \\
 & & & & & & CH_2 & - & CH_2 & - & CH_2 & - & CH_3 & &
\end{array}$$

11.53 Draw a condensed structural formula for each of the following compounds:

a. 3-ethylpentane

b. 2,2-dimethylbutane

c. 4-ethyl-3,3-dimethyl-5-propyldecane

d. 5-*sec*-butyldecane

11.54 Draw a condensed structural formula for each of the following compounds:

a. 2,2,4-trimethylpentane

b. 4-isopropyloctane

c. 3,3-diethylhexane

d. 5-*t*-butyl-2-methylnonane

11.55 Draw the condensed structural formula for each of the three structural isomers of C_5H_{12}, and give the correct IUPAC names.

11.56* Isooctane is 2,2,4-trimethylpentane. Draw the structural formula and name a branched heptane, hexane, pentane, and butane; which are structural isomers of isooctane.

11.57* Draw structural formulas for the compounds and give correct IUPAC names for the five structural isomers of C_6H_{14}.

11.58 The following names are incorrect, according to IUPAC rules. Draw the structural formulas and tell why each name is incorrect. Write the correct name for each compound.

a. 2,2-methylbutane

b. 4-ethyl-5-methylheptane

c. 2-ethyl-1,5-dimethylhexane

11.59 The following names are incorrect, according to IUPAC rules. Draw the structural formulas and tell why each name is incorrect. Write the correct name for each compound.

a. 1,2-dimethylpropane

b. 3,4-dimethylpentane

c. 2-ethyl-4-methylpentane

d. 2-bromo-3-ethylbutane

Cycloalkanes (Section 11.8)

11.60 The general formula for alkanes is C_nH_{2n+2}. Write a general formula for cycloalkanes.

11.61 Using the general formula for a cycloalkane (Exercise 11.60), calculate the following:

a. The number of hydrogen atoms present in cycloheptane.

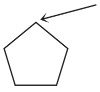
b. The number of carbon atoms present in a cycloalkane with 20 hydrogen atoms.

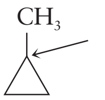
11.62 Using the general formula for a cycloalkane (Exercise 11.60), calculate the following:

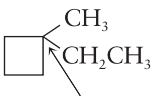
a. The number of hydrogen atoms present in cyclononane.

b. The number of carbon atoms present in a cycloalkane with 24 hydrogen atoms.

11.63 Identify how many hydrogen atoms are attached (but not shown) at each of the designated carbon atoms in the following structures:

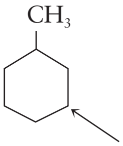
a. 

b. 

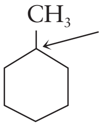
c. 

11.64 Identify how many hydrogen atoms are attached (but not shown) at each of the designated carbon atoms in the following structures:

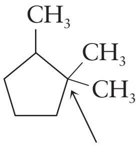
a.



b.

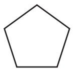


c.

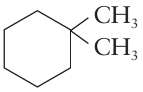


11.65 Write the correct IUPAC name for each of the following:

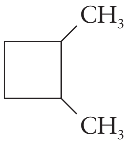
a.



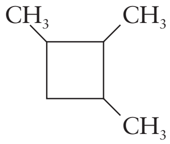
c.



b.

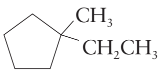


d.

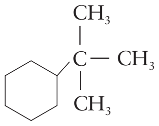


11.66 Write the correct IUPAC name for each of the following:

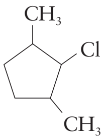
a.



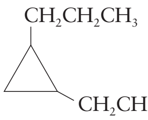
b.



c.



d.



11.67 Draw the structural formulas corresponding to each of the following IUPAC names:

a. ethylcyclobutane

b. 1,1,2,5-tetramethylcyclohexane

c. 1-butyl-3-isopropylcyclopentane

11.68 Draw the structural formulas corresponding to each of the following IUPAC names:

a. 1-ethyl-1-propylcyclopentane

b. isopropylcyclobutane

c. 1,2-dimethylcyclopropane

11.69 The following names are incorrect, according to IUPAC rules. Draw the structural formulas, and explain why each name is incorrect. Write the correct name for each compound.

a. dimethylcyclopentane

b. 2-ethyl-1-methylcyclohexane

c. 3,4-dimethylcyclohexane

d. 1,2,2-trimethylcyclobutane

11.70 The following names are incorrect, according to IUPAC rules. Draw the structural formulas, and explain why each name is incorrect. Write the correct name for each compound.

a. dimethylcyclopropane

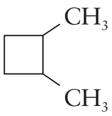
b. 1-propyl-2-ethylcyclopentane

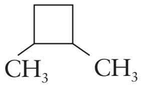
c. 2,4-dimethylcyclobutane

d. 1,2,2-trimethylcyclopentane

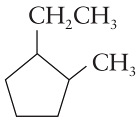
11.71 Which of the following pairs of cycloalkanes represent structural isomers?

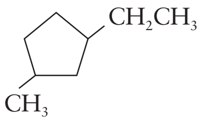
a.



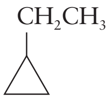


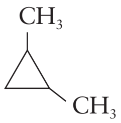
b.



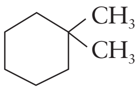


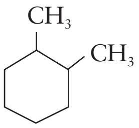
c.





d.





11.72* Draw structural formulas for the five structural isomers of C_5H_{10} that are cycloalkanes.

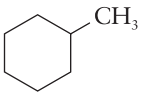
The Shape of Cycloalkanes (Section 11.9)

11.73 Why does cyclohexane assume a chair form rather than a planar hexagon?

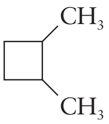
11.74 Explain the difference between *cis-trans* and structural isomers.

11.75 Which of the following cycloalkanes could show *cis-trans* isomerism? For each that could, draw structural formulas, and name both the *cis-* and the *trans-* isomers.

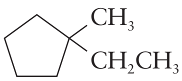
a.



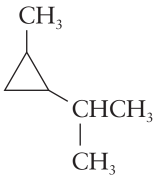
c.



b.



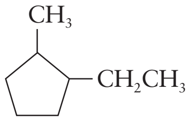
d.



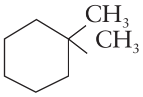
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

11.76 Which of the following cycloalkanes could show *cis-trans* isomerism? For each that could, draw structural formulas and name both the *cis-* and the *trans-* isomers.

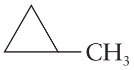
a.



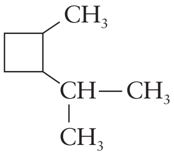
b.



c.



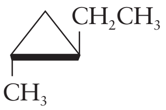
d.



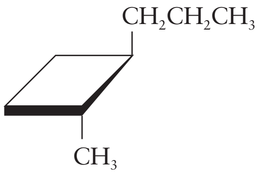
11.77 Draw structural formulas for *cis-* and *trans*-1,2-dimethylcyclohexane.

11.78 Using the prefix *cis-* or *trans-*, name each of the following:

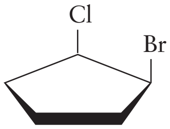
a.



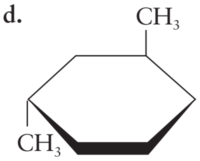
c.



b.



d.



11.79 For each of the following molecular formulas, give the structural formulas requested. In most cases, there are several possible structures.

a. C_6H_{14}, a normal alkane

b. C_6H_{14}, a branched alkane

c. C_5H_{12}, a pair of conformations

d. C_5H_{12}, a pair of structural isomers

e. C_5H_{10}, a cyclic hydrocarbon

f. C_6H_{12}, two cycloalkane *cis-trans* isomers

g. C_6H_{12}, a cycloalkane that has no *cis-trans* isomers

Physical Properties of Alkanes (Section 11.10)

11.80 The compound decane is a straight-chain alkane. Predict the following:

a. Is decane a solid, liquid, or gas at room temperature?

b. Is it soluble in water?

c. Is it soluble in hexane?

d. Is it more or less dense than water?

11.81 Explain why alkanes of low molecular weight have lower melting and boiling points than water.

11.82 Suppose you have a sample of 2-methylhexane and a sample of 2-methylheptane. Which sample would you expect to have the higher melting point? Boiling point?

11.83 Which alkane in each of the following pairs of compounds has the higher boiling point?

a. ethane and propane

b. hexane and pentane

11.84 Which alkane in each of the following pairs of compounds has the higher boiling point?

a. butane and hexane

b. decane and octane

11.85 Identify the physical state (solid, liquid, or gas) at room temperature and pressure for each of the following alkanes:

a. hexane

b. butane

c. $C_{11}H_{24}$

11.86 Identify the physical state (solid, liquid, or gas) at room temperature and pressure for each of the following alkanes:

a. propane

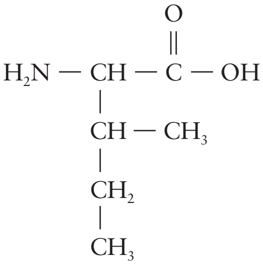
b. $C_{24}H_{50}$

c. $C_{18}H_{30}$

11.87 Petroleum jelly is used to treat or prevent minor skin irritations such as diaper rash. Explain how the hydrophobic properties of petroleum jelly could be demonstrated.

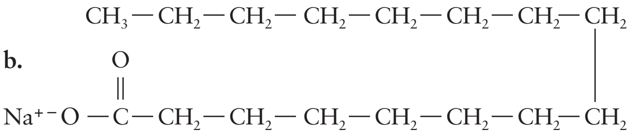
11.88 Identify (circle) the alkane-like portions of the following molecules:

a.



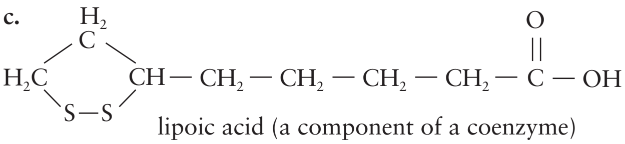
isoleucine (an amino acid)

b.



sodium palmitate (a soap)

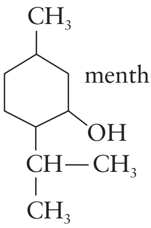
c.



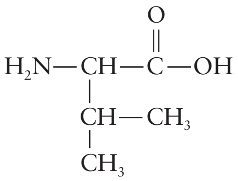
lipoic acid (a component of a coenzyme)

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

11.89 Identify (circle) the alkane-like portions of the following molecules:

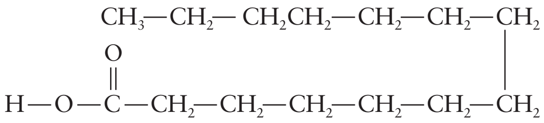
a. 

menthol (a flavoring)

b. 

$$H_2N-\underset{\substack{|\\ CH-CH_3\\ |\\ CH_3}}{CH}-\overset{\substack{O\\ ||}}{C}-OH$$

valine (an essential component of proteins)

c. 

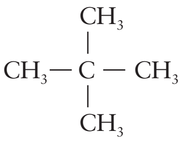
$$\begin{array}{l} CH_3-CH_2-CH_2CH_2-CH_2-CH_2-CH_2 \\ \qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\quad | \\ H-O-\overset{\substack{O\\ ||}}{C}-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2 \end{array}$$

myristic acid (component of coconut oil)

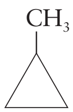
Alkane Reactions (Section 11.11)

11.90 Write a balanced equation to represent the complete combustion of each of the following:

a. Butane

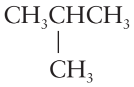
b. 

$$CH_3-\underset{\substack{|\\ CH_3}}{\overset{\substack{CH_3\\ |}}{C}}-CH_3$$

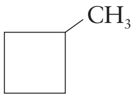
c. 

11.91 Write a balanced equation to represent the complete combustion of each of the following:

a. Propane

b. 

$$CH_3\underset{\substack{|\\ CH_3}}{CH}CH_3$$

c. 

11.92 Write a balanced equation for the incomplete combustion of hexane, assuming the formation of carbon monoxide and water as the products.

11.93 Why is it dangerous to relight a furnace when a foul odor is present?

Additional Exercises

11.94 Using the concept of dispersion forces, explain why most cycloalkanes have higher boiling points than normal alkanes with the same number of carbon atoms.

11.95 Draw a Lewis electron dot formula for ethane (CH_3-CH_3). Explain why ethane molecules do not form a hydrogen-bond.

11.96 Your sometimes inept lab technician performed experiments to determine the vapor pressure of pentane, hexane, and heptane at 20°C. He gave you back the numbers of 113.9, 37.2, and 414.5 torr without identifying the compounds. Which vapor pressure value goes with which compound?

11.97 How many grams of water will be produced by the complete combustion of 10.0 g of methane (CH_4)?

11.98 How many liters of air at STP are needed to completely combust 1.00 g of methane (CH_4)? Air is composed of about 21% v/v oxygen (O_2).

Chemistry for Thought

11.99 Would you expect a molecule of urea produced in the body to have any different physical or chemical properties from a molecule of urea prepared in a laboratory?

11.100 Why might the study of organic compounds be important to someone interested in the health or life sciences?

11.101 Why do very few aqueous solutions of organic compounds conduct electricity?

11.102 The ski wax being examined in **Figure 11.3** has a relatively low melting point. What does that fact reveal about the forces between molecules?

11.103 Charcoal briquettes sometimes burn with incomplete combustion when the air supply is limited. Why would it be hazardous to place a charcoal grill inside a home or a camper in an attempt to keep warm?

11.104 If carbon did not form hybridized orbitals, what would you expect to be the formula of the simplest compound of carbon and hydrogen?

11.105 What types of sports equipment are made from graphite fibers besides that shown in **Figure 11.12**?

11.106 A semi truck loaded with cyclohexane overturns during a rainstorm, spilling its contents over the road embankment. If the rain continues, what will be the fate of the cyclohexane?

11.107 On the way home from school, you drove through a construction zone, resulting in several tar deposits on the car's fender. What substances commonly found in the kitchen might help in removing the tar deposits?

11.108 Oil spills along coastal shores can be disastrous to the environment. What physical and chemical properties of alkanes contribute to the consequences of an oil spill?

11.109 Why might some farmers hesitate to grow and sell organic produce?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

12 Unsaturated Hydrocarbons

Antonio Marquez lanza/Moment/Getty Images

Health Career Focus

ANESTHESIOLOGIST ASSISTANT

"Consider how lucky we are to live in a modern country at this point in time," I said to my friend over coffee. "Anesthesia, as we know it, has existed for less than 200 years! Can you imagine the world without it?"

"Yes, I sure can," my friend replied with a shudder. "But, I don't really like to!"

By working as an anesthesiologist assistant, I feel that every day I give the greatest possible gift to my patients. It's awe inspiring to consider what the scientific application of a few gases and medications applied with skill makes possible—pain-free procedures and surgeries. What an amazing gift!

I considered pre-med in college, but I thought a doctor's schedule and responsibilities just weren't for me. I found that I could get the same sense of satisfaction working as an anesthesiologist assistant. I know I'm an important part of the surgical team. Eliminating pain—what could be better?

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Classify unsaturated hydrocarbons as alkenes, alkynes, or aromatics. **(Section 12.1)**
2. Write the International Union of Pure and Applied Chemistry (IUPAC) names of alkenes from their molecular structures. **(Section 12.1)**
3. Predict the existence of *cis-trans* isomers from formulas of compounds. **(Section 12.2)**
4. Write the names and structural formulas for *cis-trans* isomers. **(Section 12.2)**
5. Write equations for addition reactions of alkenes, and use Markovnikov's rule to predict the major products of certain reactions. **(Section 12.3)**

6 Write equations for addition polymerization, and list uses for addition polymers. **(Section 12.4)**

7 Write the IUPAC names of alkynes from their molecular structures. **(Section 12.5)**

8 Classify organic compounds as aliphatic or aromatic. **(Section 12.6)**

9 Name and draw structural formulas for aromatic compounds. **(Section 12.7)**

10 Recognize uses for specific aromatic compounds. **(Section 12.8)**

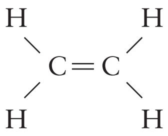
AN UNSATURATED HYDROCARBON contains one or more double or triple bonds between carbon atoms and belongs to one of three classes: alkenes, alkynes, or aromatic hydrocarbons. An **alkene** contains one or more double bonds, an **alkyne** contains one or more triple bonds, and an **aromatic hydrocarbon** contains three double bonds alternating with three single bonds in a six-carbon ring. Ethylene (the simplest alkene), acetylene (the simplest alkyne), and benzene (the simplest aromatic) are represented by the following structural formulas:

unsaturated hydrocarbon A hydrocarbon containing one or more multiple bonds.

alkene A hydrocarbon containing one or more double bonds.

alkyne A hydrocarbon containing one or more triple bonds.

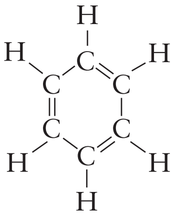
aromatic hydrocarbon Any organic compound that contains the characteristic benzene ring or similar feature.



ethylene
(an alkene)

$H-C\equiv C-H$

acetylene
(an alkyne)



benzene
(an aromatic)

Alkenes and alkynes are called *unsaturated* because more hydrogen atoms can be added in somewhat the same sense that more solute can be added to an unsaturated solution. Benzene and other aromatic hydrocarbons also react to add hydrogen atoms; in general, however, they have chemical properties very different from those of alkenes and alkynes.

Robert Fried/Alamy Stock Photo

FIGURE 12.1 Ethylene (ethene), a plant hormone that controls growth and fruit development, is used commercially for artificial ripening of fruits.

12.1 The Nomenclature of Alkenes

Learning Objective 1 Classify unsaturated hydrocarbons as alkenes, alkynes, or aromatics.

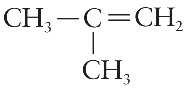
Learning Objective 2 Write the IUPAC names of alkenes from their molecular structure.

The general formula for alkenes is C_nH_{2n} (the same as that for cycloalkanes). The simplest members are well known by their common names, ethylene (see **Figure 12.1**) and propylene:

$$\underset{\text{ethylene, } C_2H_4}{CH_2{=}CH_2} \qquad \underset{\text{propylene, } C_3H_6}{CH_3{-}CH{=}CH_2}$$

Three structural isomers have the formula C_4H_8:

$$CH_3{-}CH_2{-}CH{=}CH_2 \qquad CH_3{-}CH{=}CH{-}CH_3$$



$$CH_3{-}\underset{\displaystyle CH_3}{\underset{|}{C}}{=}CH_2$$

The number of structural isomers increases rapidly as the number of carbons increases because, besides variations in chain length and branching, variations occur in the position of the double bond. IUPAC nomenclature is extremely useful in differentiating among these many alkene compounds.

The IUPAC rules for naming alkenes are similar to those used for the alkanes, with a few additions to indicate the presence and location of double bonds.

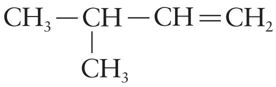
STEP 1. Name the longest chain that contains the double bond. The suffix name of the compound is *-ene*.
STEP 2. Number the longest chain of carbon atoms so that the carbon atoms joined by the double bond have numbers as low as possible.
STEP 3. Locate the double bond by the lower-numbered carbon atom bound by the double bond.
STEP 4. Locate and name attached groups.
STEP 5. Combine the names for the attached groups and the longest chain into the name.

Example 12.1 Naming Alkenes

Name the following alkenes:

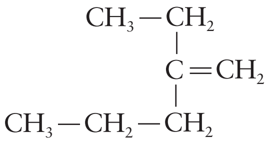
a. $CH_3{-}CH{=}CH{-}CH_3$

b.



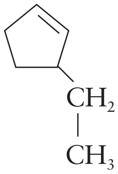
$$CH_3{-}\underset{\displaystyle CH_3}{\underset{|}{CH}}{-}CH{=}CH_2$$

c.



$$\begin{array}{l} \qquad\quad CH_3{-}CH_2 \\ \qquad\qquad\qquad\ \ | \\ \qquad\qquad\qquad\ C{=}CH_2 \\ \qquad\qquad\qquad\ \ | \\ CH_3{-}CH_2{-}CH_2 \end{array}$$

d.



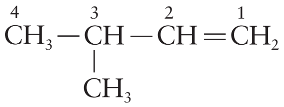
Solution

a. The longest chain containing a double bond has four carbon atoms. The four-carbon alkane is butane. Thus, the compound is a butene:

$$\overset{1}{CH_3}{-}\overset{2}{CH}{=}\overset{3}{CH}{-}\overset{4}{CH_3}$$

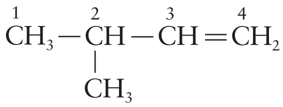
The chain can be numbered from either end because the double bond will be between carbons 2 and 3 either way. The position of the double bond is indicated by the lower-numbered carbon atom that is double-bonded, carbon 2 in this case. The name is 2-butene.

b. To give lower numbers to the carbons bound by the double bond, the chain is numbered from the right:



$$\overset{4}{CH_3}-\underset{\substack{|\\ CH_3}}{\overset{3}{CH}}-\overset{2}{CH}=\overset{1}{CH_2}$$

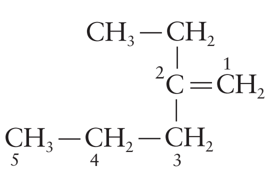
not



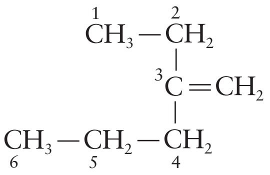
$$\overset{1}{CH_3}-\underset{\substack{|\\ CH_3}}{\overset{2}{CH}}-\overset{3}{CH}=\overset{4}{CH_2}$$

Thus, the compound is a 1-butene with an attached methyl group on carbon 3. Therefore, the name is 3-methyl-1-butene.

c. Care must be taken to select the longest chain containing the double bond. This compound is named as a pentene and not as a hexene because the double bond is not contained in the six-carbon chain:

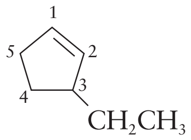


not



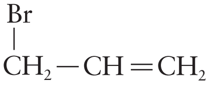
The compound is a 1-pentene with an ethyl group at position 2. Therefore, the name is 2-ethyl-1-pentene.

d. In cyclic alkenes, the ring is numbered so as to give the lowest possible numbers to the double-bonded carbons (they become carbons 1 and 2). The numbering direction around the ring is chosen so that attached groups are located on the lowest-numbered carbon atoms possible. Thus, the name is 3-ethylcyclopentene:

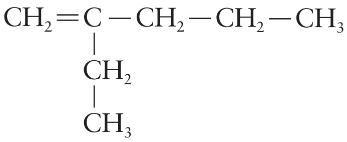


Notice that it is not called 3-ethyl-1-cyclopentene because the double bond is always between carbons 1 and 2, and therefore its position need not be indicated.

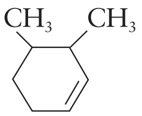
✔ LEARNING CHECK 12.1 Give the IUPAC name for each of the following:

a. 

$$\overset{\substack{Br\\ |}}{CH_2}-CH=CH_2$$

b. 

$$CH_2=\underset{\substack{|\\ CH_2\\ |\\ CH_3}}{C}-CH_2-CH_2-CH_3$$

c. 

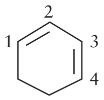
Some compounds contain more than one double bond per molecule (see **Figure 12.2**). Molecules of this type are important components of natural and synthetic rubber and other useful materials. The nomenclature of these compounds is the same as for the alkenes with one double bond, except that the endings *-diene, -triene*, and the like are used to denote the number of double bonds. Also, the locations of all the multiple bonds must be indicated in all molecules, including those with rings:

valentinrussanov/iStock/Getty Images

FIGURE 12.2 β-carotene, the compound responsible for the orange color of carrots and yams, contains ten double bonds.

$$\overset{1}{CH_2}=\overset{2}{CH}-\overset{3}{CH}=\overset{4}{CH_2}$$

1,3-butadiene

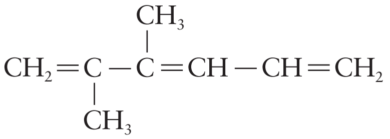


1,3-cyclohexadiene

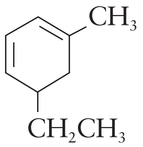
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 12.2 More Naming Alkenes

Name the following compounds:

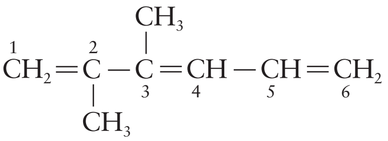
a. 

$CH_2{=}\underset{\displaystyle CH_3}{C}{-}\overset{\displaystyle CH_3}{C}{=}CH{-}CH{=}CH_2$

b. 

Solution

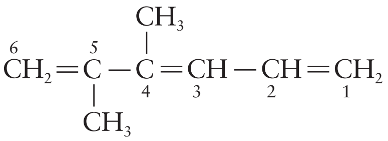
a. This compound is a methyl-substituted hexatriene. The chain is numbered from the end nearest to the branch because the direction of numbering, again, makes no difference in locating the double bonds correctly. The name is 2,3-dimethyl-1,3,5-hexatriene:



$\overset{1}{CH_2}{=}\overset{2}{\underset{\displaystyle CH_3}{C}}{-}\underset{3}{\overset{\displaystyle CH_3}{C}}{=}\underset{4}{CH}{-}\underset{5}{CH}{=}\underset{6}{CH_2}$

2,3-dimethyl-1,3,5-hexatriene

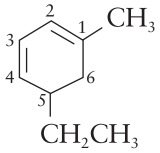
and not



$\overset{6}{CH_2}{=}\overset{5}{\underset{\displaystyle CH_3}{C}}{-}\underset{4}{\overset{\displaystyle CH_3}{C}}{=}\underset{3}{CH}{-}\underset{2}{CH}{=}\underset{1}{CH_2}$

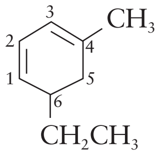
4,5-dimethyl-1,3,5-hexatriene

b. This compound is a substituted cyclohexadiene. The ring is numbered as shown. The name is 5-ethyl-1-methyl-1,3-cyclohexadiene:



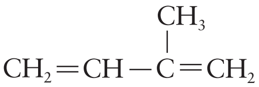
5-ethyl-1-methyl-1,3-cyclohexadiene

and not

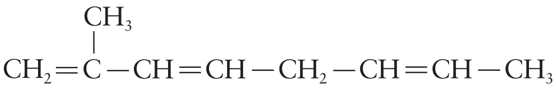


6-ethyl-4-methyl-1,3-cyclohexadiene

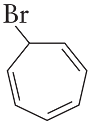
✔ **LEARNING CHECK 12.2** Give the IUPAC name for each of the following:

a. 

$CH_2{=}CH{-}\overset{\displaystyle CH_3}{C}{=}CH_2$

b. 

$CH_2{=}\overset{\displaystyle CH_3}{C}{-}CH{=}CH{-}CH_2{-}CH{=}CH{-}CH_3$

c. 

12.2 The Geometry of Alkenes

Learning Objective 3 Predict the existence of *cis-trans* isomers from formulas of compounds.

Learning Objective 4 Write the names and structural formulas for *cis-trans* isomers.

The hybridization of atomic orbitals discussed in **Section 11.3** to explain the bonding characteristics of carbon atoms bonded to four other atoms can also be used to describe alkenes, compounds in which some carbon atoms are bonded to only three atoms. This hybridization involves mixing a 2*s* orbital and two 2*p* orbitals of a carbon atom to form three hybrid sp^2 orbitals (see **Figure 12.3**).

The three sp^2 hybrid orbitals lie in the same plane and are separated by angles of 120°. The unhybridized 2*p* orbital of the carbon atom is located perpendicular to the plane of the sp^2 hybrid orbitals (see **Figure 12.4**).

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

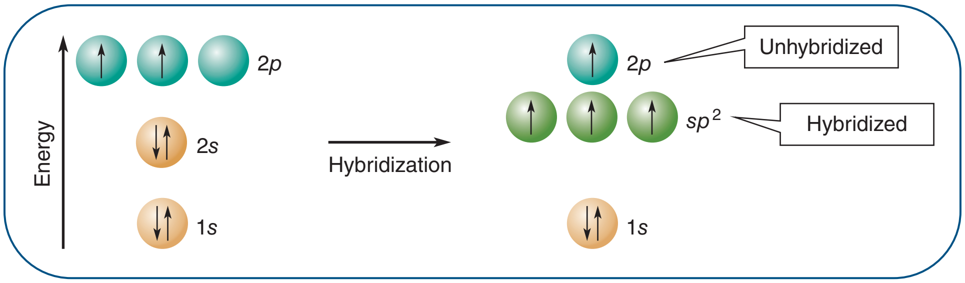

Energy
2p
2s
1s
Hybridization
2p
Unhybridized
sp2
Hybridized
1s

FIGURE 12.3 A representation of sp^2 hybridization of carbon. During hybridization, two of the 2*p* orbitals mix with the single 2*s* orbital to produce three sp^2 hybrid orbitals. One 2*p* orbital is not hybridized and remains unchanged.

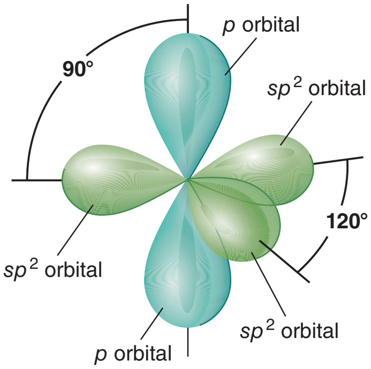

p orbital
90°
sp2 orbital
120°
sp2 orbital
sp2 orbital
p orbital

FIGURE 12.4 The unhybridized *p* orbital is perpendicular to the plane of the three sp^2 hybridized orbitals.

The bonding between the carbon atoms of ethylene results partially from the overlap of one sp^2 hybrid orbital of each carbon to form a sigma (σ) bond. The second carbon–carbon bond is formed when the unhybridized 2*p* orbitals of the carbons overlap sideways to form what is called a pi (π) bond. The remaining two sp^2 hybrid orbitals of each carbon overlap with the 1*s* orbitals of the hydrogen atoms to form sigma bonds. Thus, each ethylene molecule contains five sigma bonds (one carbon–carbon and four carbon–hydrogen) and one pi bond (carbon–carbon), as shown in **Figure 12.5**.

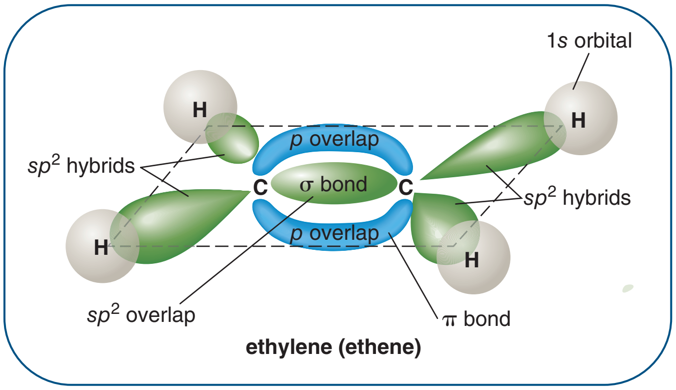

1s orbital
H
p overlap
H
sp2 hybrids
C
σ bond
C
sp2 hybrids
H
p overlap
H
sp2 overlap
π bond
ethylene (ethene)

FIGURE 12.5 The bonding in ethylene is explained by combining two sp^2 hybridized carbon atoms. The C—H sigma bonds all lie in the same plane. The unhybridized *p* orbitals of the carbon atoms overlap above and below the molecular plane to form the pi bond.

Experimental data support this hybridization model. Ethylene has been found to be a planar molecule with bond angles close to 120° between the atoms (see **Figure 12.6**).

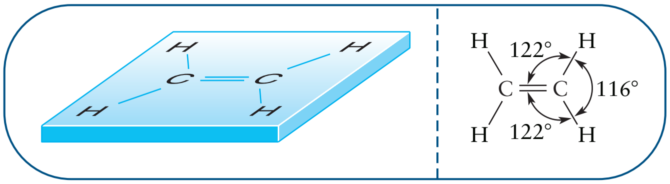
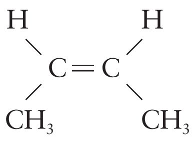
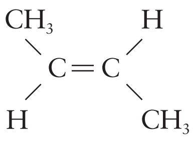

H
H
C
C
H
H
H
122°
H
C
C
116°
H
122°
H

FIGURE 12.6 All six atoms of ethylene lie in the same plane.

In addition to geometry, alkenes also differ from open-chain alkanes in that the double bonds prevent the relatively free rotation that is characteristic of carbon atoms bonded by single bonds. As a result, alkenes can exhibit *cis-trans* isomerism, the same type of stereoisomerism seen earlier for the cycloalkanes (see **Section 11.9**). There are two *cis-trans* isomers of 2-butene:


H
H
C
C
CH3
CH3

cis-2-butene


CH3
H
C
C
H
CH3

trans-2-butene

HEALTH CONNECTIONS **12.1**

Three-Dimensional Printers

We are all familiar with copiers that can make two-dimensional copies of a printed page. In these copiers, computer-controlled printer heads move horizontally, printing a one-dimensional line at a time. Eventually (and quite quickly) this creates many side-by-side lines which form the two-dimensional image or line of printed letters. This is somewhat like laying narrow, thin bricks end to end and side by side to form a narrow wall.

A three-dimensional printer works somewhat like a two-dimensional printer, with one big difference. After laying down one line like a two-dimensional printer, the three-dimensional printer lays a second line on top of the first line, giving it a thickness. In the brick walk analogy, this would be the equivalent of laying a second row of bricks on top of the first row to begin forming a wall.

The "ink" used in 3-D printers is often a plastic with a specific melting point. The plastic comes wound on spools, and the 3-D printer heads heat the end of the plastic just enough to melt it so it can form a thin line. Multiple lines laid side by side form a layer. Layers laid on top of one another form an object with thickness. The computer controls these operations to give objects of the desired length, width, and thickness. Vitally important medical uses of 3-D printing include tissue and organ fabrication, creating prosthetics and implants, and building realistic anatomical models.

100%
3D PRINTING
COMPLETE
LAYERS

Scharfsinn/Shutterstock.com

A 3-D printer can build a model of a human heart or other organs.

coffeekai/iStock/Getty Images

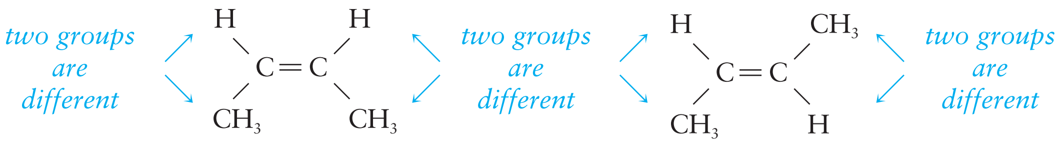
FIGURE 12.7 The unsaturated components in vegetable oils contain *cis* double bonds, which contribute to making the material a liquid at room temperature.

Once again, the prefix *cis*- is used for the isomer in which the two similar or identical groups are on the same side of the double bond and *trans*- for the one in which they are on opposite sides. The two isomers *cis*- and *trans*-2-butene represent distinctly different compounds with different physical properties (see **Table 12.1** and **Figure 12.7**).

TABLE 12.1 Physical Properties of a Pair of *Cis-trans* Isomers

Isomer	Melting Point (°C)	Boiling Point (°C)	Density (g/mL)
cis-2-butene	−139.9	3.7	0.62
trans-2-butene	−105.6	0.9	0.60

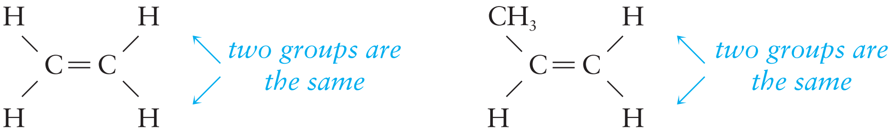
Not all double-bonded compounds show *cis-trans* stereoisomerism. *Cis-trans* stereoisomerism is found only in alkenes that have two different groups attached to each double-bonded carbon atom. In 2-butene, the two different groups are a methyl and a hydrogen for each double-bonded carbon:



cis-2-butene

trans-2-butene

If either double-bonded carbon is attached to identical groups, no *cis-trans* isomers are possible. Thus, there are no *cis-trans* isomers of ethene or propene:

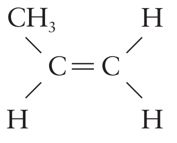


ethene

propene

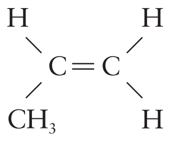
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

To see why this is so, let's try to draw *cis-trans* isomers of propene:



(A)

is the same as



(B)

Notice that structure (B) can be converted into (A) by just flipping it over. Thus, they are identical and not isomers.

Example 12.3 Drawing *Cis-Trans* Isomers

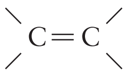
Cis-trans isomerism plays an essential role in many biological processes, including the response to light by the retina of the eye.

Determine which of the following molecules can exhibit *cis-trans* isomerism, and draw structural formulas to illustrate your conclusions:

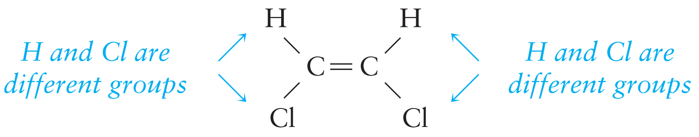
a. $Cl-CH=CH-Cl$
b. $CH_2=CH-Cl$
c. $Cl-CH=CH-CH_3$

Solution

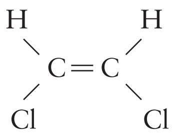
a. Begin by drawing the carbon–carbon double bond with bond angles of 120° about each carbon atom:



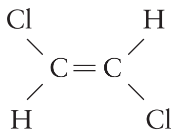
Next, complete the structure and analyze each carbon of the double bond to see if it is attached to two different groups:



In this case, each carbon is attached to two different groups and *cis-trans* isomers are possible:

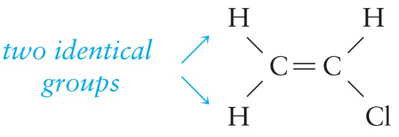


cis

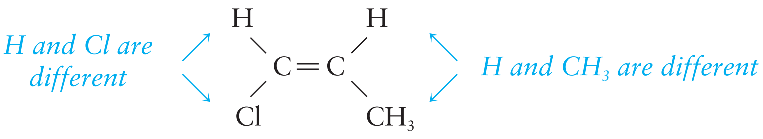


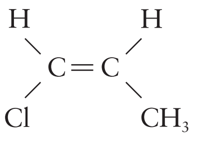
trans

b. No *cis-trans* isomers are possible because one carbon contains two identical groups:

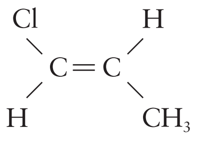


c. *Cis-trans* isomers are possible because there are two different groups on each carbon:





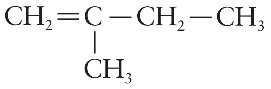
cis-1-chloropropene

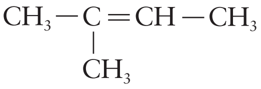


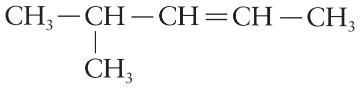
trans-1-chloropropene

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

✔ LEARNING CHECK 12.3 Determine which of the following can exhibit *cis-trans* isomerism, and draw structural formulas for the *cis* and *trans* isomers of those that can:

a. 
$CH_2{=}\underset{\displaystyle CH_3}{\underset{|}{C}}{-}CH_2{-}CH_3$

c. 
$CH_3{-}\underset{\displaystyle CH_3}{\underset{|}{C}}{=}CH{-}CH_3$

b. 
$CH_3{-}\underset{\displaystyle CH_3}{\underset{|}{CH}}{-}CH{=}CH{-}CH_3$

12.3 Properties of Alkenes

Learning Objective 5 Write equations for addition reactions of alkenes, and use Markovnikov's rule to predict the major products of certain reactions.

12.3A Physical Properties

The alkenes are similar to the alkanes in physical properties—they are nonpolar compounds that are insoluble in water, soluble in nonpolar solvents, and less dense than water (see **Table 12.2** and **Figure 12.8**). Alkenes containing 4 carbon atoms or fewer are gases under ordinary conditions. Those containing 5 to 17 carbon atoms are liquids, and those with 18 or more carbon atoms are solids. Low molecular weight alkenes have somewhat unpleasant, gasoline-like odors.

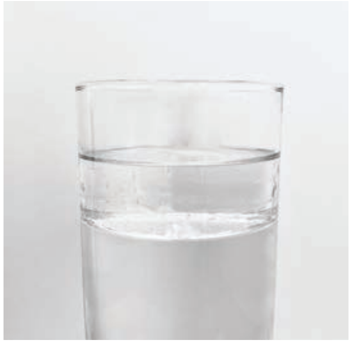
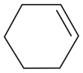

Michael Slabaugh

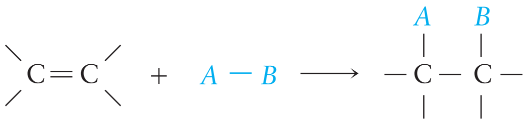
FIGURE 12.8 A mixture of alkene (1-hexene) and water. Alkenes are nonpolar and less dense than water, so they form a separate layer on top of the water layer.

TABLE 12.2 Physical Properties of Some Alkenes

IUPAC Name	Structural Formula	Boiling Point (°C)	Melting Point (°C)	Density (g/mL)
Ethene	$CH_2{=}CH_2$	−104	−169	0.38
Propene	$CH_2{=}CHCH_3$	−47	−185	0.52
1-butene	$CH_2{=}CHCH_2CH_3$	−6	−185	0.60
1-pentene	$CH_2{=}CHCH_2CH_2CH_3$	30	−138	0.64
1-hexene	$CH_2{=}CHCH_2CH_2CH_2CH_3$	63	−140	0.67
Cyclohexene		83	−104	0.81

12.3B Chemical Properties

In contrast to alkanes, which are inert to almost all chemical reagents (see **Section 11.11**), alkenes are quite reactive chemically. Since the only difference between an alkane and an alkene is the double bond, it is not surprising to learn that most of the reactions of alkenes take place at the double bond. These reactions follow the pattern:



(12.1)

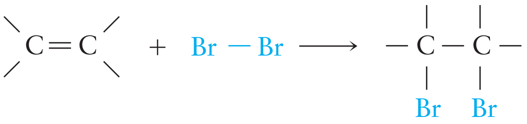
These are called **addition reactions**, because a substance is added to the double bond. Addition reactions are characterized by two reactants that combine to form one product.

Halogenation is one of the most common addition reactions. For example, when bromine, a halogen, is added to an alkene, the double bond reacts, and only a carbon–carbon single bond remains in the product. Without a double bond present, the product is referred to as a **haloalkane** or **alkyl halide**. Reaction 12.2 gives the general reaction, and Reaction 12.3 is a specific example, the bromination of 1-butene.

addition reaction A reaction in which a compound adds to a multiple bond.

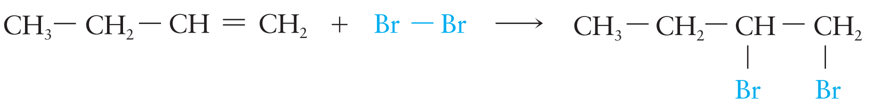
haloalkane or **alkyl halide** A derivative of an alkane in which one or more hydrogens are replaced by halogens.

General reaction:



$$>C=C< + Br-Br \longrightarrow -\underset{Br}{\overset{|}{\underset{|}{C}}}-\underset{Br}{\overset{|}{\underset{|}{C}}}- \qquad (12.2)$$

Specific example:

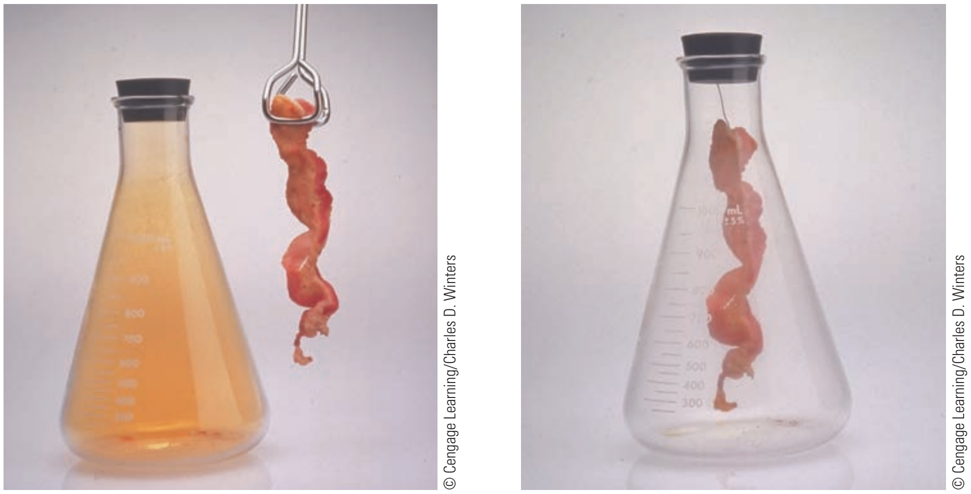


$$CH_3-CH_2-CH=CH_2 + Br-Br \longrightarrow CH_3-CH_2-\underset{Br}{\underset{|}{CH}}-\underset{Br}{\underset{|}{CH_2}} \qquad (12.3)$$

1-butene

1,2-dibromobutane

The addition of Br_2 to double bonds provides a simple laboratory test for unsaturation (see **Figure 12.9**). As the addition takes place, the characteristic red-brown color of the added bromine fades as it is used up, and the colorless dibromoalkane product forms.



© Cengage Learning/Charles D. Winters

© Cengage Learning/Charles D. Winters

1 The bromine vapor in the flask has a red brown color. The fat in bacon is partially unsaturated.

2 The bromine vapor loses its red brown color when it reacts with the unsaturated bacon fat.

FIGURE 12.9 The reaction of bromine with an unsaturated hydrocarbon.

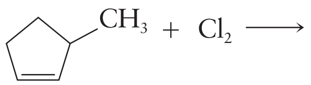
The addition of halogens is also used to quantitatively determine the degree of unsaturation in vegetable oils, margarines, and shortenings (see **Section 18.4**). Chlorine reacts with alkenes to give dichloro products in an addition reaction similar to that of bromine. However, it is not used as a test for unsaturation because it is difficult to see the pale green color of chlorine in solution.

Example 12.4 Writing Halogenation Reactions

Halogenated compounds are rare in living forms. This partly explains the impact of halogenated insecticides such as DDT on the environment (see **Figure 12.10**). Write the structural formula for the product of each of the following reactions:

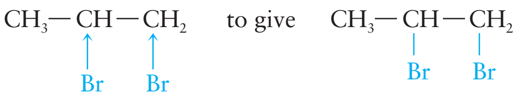
a. $CH_3-CH=CH_2 + Br_2 \longrightarrow$

b.



Solution

a. In an addition reaction, the carbon–carbon double bond is converted to a single bond. The other reactant (Br_2) attaches to the carbon atoms that were part of the double bond.



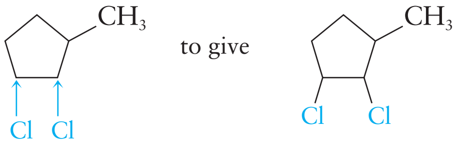
$$CH_3-\underset{Br}{\underset{\uparrow}{CH}}-\underset{Br}{\underset{\uparrow}{CH_2}} \quad \text{to give} \quad CH_3-\underset{Br}{\underset{|}{CH}}-\underset{Br}{\underset{|}{CH_2}}$$

Ron Harvey/Everett Collection Historical/Alamy Stock Photo

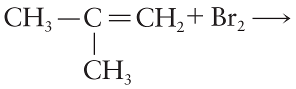
FIGURE 12.10 Biologist Rachel Carson alerted the world to the environmental impact of fertilizers and pesticides in her book *Silent Spring*.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

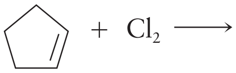
b. Cyclic alkenes undergo the same addition reaction, as the double bond is converted to a single bond.



✔ LEARNING CHECK 12.4 Write the structural formula for the product of each of the following reactions:

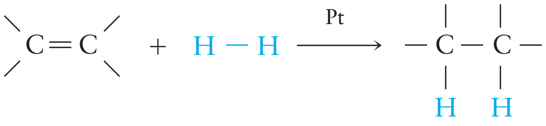
a. 

$$CH_3-\underset{\displaystyle CH_3}{\underset{|}{C}}=CH_2+Br_2\longrightarrow$$

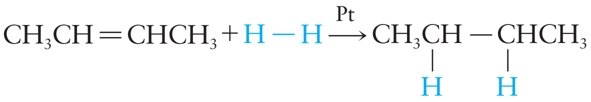
b.  + Cl_2 ⟶

In the presence of an appropriate catalyst (such as platinum, palladium, or nickel), hydrogen adds to alkenes and converts them into the corresponding alkanes. This reaction, which is called **hydrogenation**, is illustrated in Reactions 12.4 and 12.5.

hydrogenation A reaction in which the addition of hydrogen takes place.

General reaction:  (12.4)

an alkane

Specific example:  (12.5)

$$CH_3CH=CHCH_3+H-H\xrightarrow{Pt}CH_3\underset{\displaystyle H}{\underset{|}{CH}}-\underset{\displaystyle H}{\underset{|}{CH}}CH_3$$

2-butene butane

The hydrogenation of vegetable oils is a very important commercial process. Vegetable oils, such as soybean and cottonseed oil, are composed of long-chain organic molecules that contain many alkene bonds. The high degree of unsaturation characteristic of these oils gave rise to the term **polyunsaturated**. Upon hydrogenation, the melting point of the oils is raised, and the oils become low-melting-point solids. These products are used in the form of margarine (see **Figure 12.11**) and shortening.

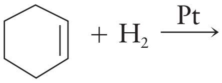
polyunsaturated A term usually applied to molecules with several double bonds.

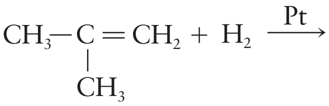
George Doyle/Stockbyte/Getty Images

FIGURE 12.11 Margarines are prepared by the hydrogenation of vegetable oils.

Example 12.5 Writing Hydrogenation Reactions

Many chemical reactions within the body require the addition of two atoms of hydrogen, but these reactions are much more complex. Write the structural formula for each of the following reactions.

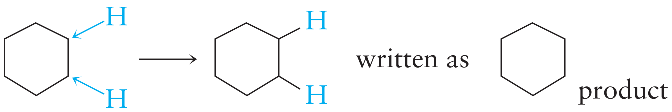
a.  + H_2 $\xrightarrow{Pt}$

b. 

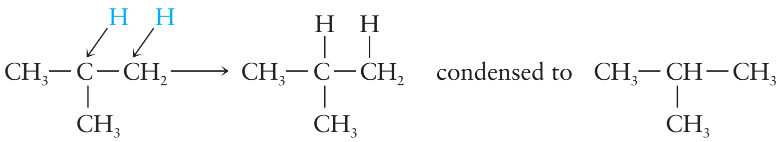
$$CH_3-\underset{\displaystyle CH_3}{\underset{|}{C}}=CH_2+H_2\xrightarrow{Pt}$$

Solution

a. In an addition reaction, the carbon–carbon double bond is converted to a single bond. The two hydrogen atoms attach to the carbon atoms that were part of the double bond. In the abbreviated structure of the product, none of the hydrogen atoms attached to ring carbon atoms are shown.

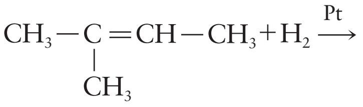


b. The carbon–carbon double bond becomes a carbon–carbon single bond with two hydrogen atoms attached.

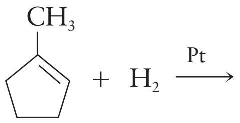


$$CH_3-\underset{CH_3}{\overset{H}{C}}-\overset{H}{CH_2} \longrightarrow CH_3-\underset{CH_3}{\overset{H}{C}}-\overset{H}{CH_2} \quad \text{condensed to} \quad CH_3-\underset{CH_3}{CH}-CH_3$$

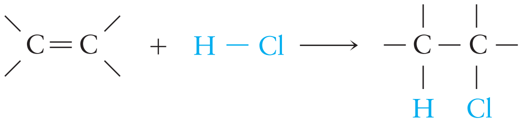
✔ **LEARNING CHECK 12.5** Write the structural formula for the product of each of the following reactions:

a. 

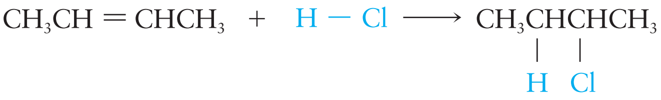
$$CH_3-\underset{CH_3}{C}=CH-CH_3+H_2 \xrightarrow{Pt}$$

b. 

A number of acidic compounds, such as the hydrogen halides—HF, HCl, HBr, and HI—also add to alkenes to give the corresponding alkyl halide. The reaction with HCl is illustrated as follows:

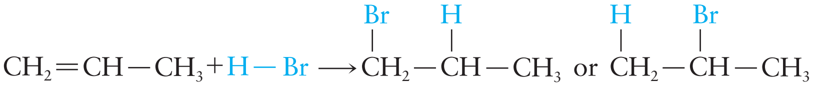
General reaction:  (12.6)

$$\rangle C=C \langle + H-Cl \longrightarrow -\underset{H}{C}-\underset{Cl}{C}-$$

Specific example:  (12.7)

$$CH_3CH=CHCH_3 + H-Cl \longrightarrow CH_3\underset{H}{CH}\underset{Cl}{CH}CH_3$$

The addition reactions involving H_2, Cl_2, and Br_2 yield only one product because the same group (H and H or Br and Br) adds to each double-bonded carbon. However, with H—X, a different group adds to each carbon, and for certain alkenes, there are two possible products. For example, in the reaction of HBr with propene, two products might be expected: 1-bromopropane or 2-bromopropane,

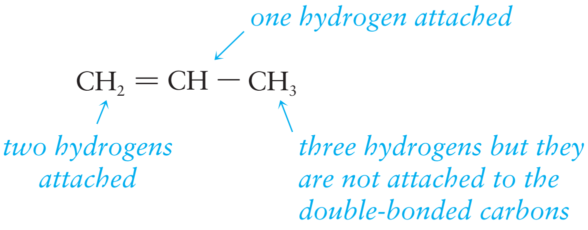
 (12.8)

$$CH_2=CH-CH_3+H-Br \longrightarrow \overset{Br}{CH_2}-\overset{H}{CH}-CH_3 \text{ or } \overset{H}{CH_2}-\overset{Br}{CH}-CH_3$$

1-bromopropane 2-bromopropane

It turns out that only one product, 2-bromopropane, is formed in significant amounts. This fact, first reported in 1869 by Russian chemist Vladimir Markovnikov, gave rise to a rule for predicting which product will be exclusively or predominantly formed. According to **Markovnikov's rule**, when a molecule of the form H—X adds to an alkene, the hydrogen becomes attached to a double-bonded carbon atom that is already bonded to more hydrogens. A phrase to help you remember this rule is "the rich get richer." Applying this rule to propene, we find:

Markovnikov's rule In the addition of H—X to an alkene, the hydrogen becomes attached to the carbon atom that is already bonded to more hydrogens.



$$CH_2=CH-CH_3$$

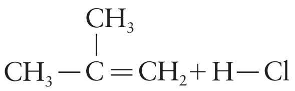
one hydrogen attached
two hydrogens attached
three hydrogens but they are not attached to the double-bonded carbons

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

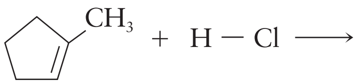
Therefore, H attaches to the end carbon of the double bond, Br attaches to the second carbon, and 2-bromopropane is the major product.

Example 12.6 Using Markovnikov's Rule

Use Markovnikov's rule to predict the major product in the following reactions:

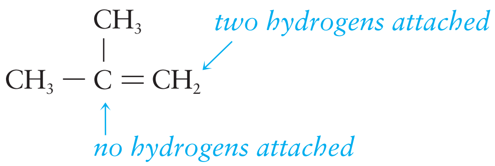
a. 

$\mathrm{CH_3-\overset{CH_3}{\overset{|}{C}}=CH_2+H-Cl}$

b. 

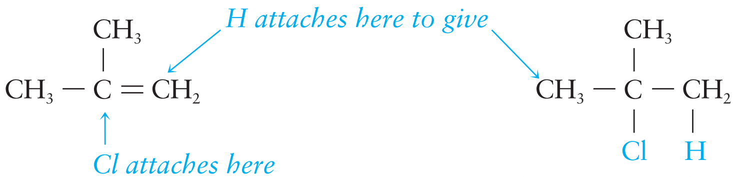
Solution

a. Analyze the C═C to see which carbon atom has more hydrogens attached:



CH$_3$
two hydrogens attached
CH$_3$ — C ═ CH$_2$
no hydrogens attached

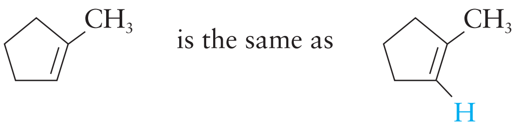
The H of H—Cl will attach to the position that has more hydrogens. Thus, 2-chloro-2-methylpropane is the major product:



CH$_3$
CH$_3$ — C ═ CH$_2$
H attaches here to give
Cl attaches here
CH$_3$
CH$_3$ — C — CH$_2$
Cl
H

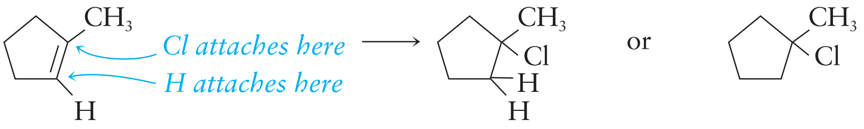
2-chloro-2-methylpropane

b. The challenge with a cyclic alkene is to remember that the hydrogens are not shown. Thus,



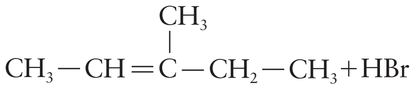
CH$_3$
is the same as
CH$_3$
H

As before, the H of H—Cl will attach to the double-bonded carbon that has more hydrogens:

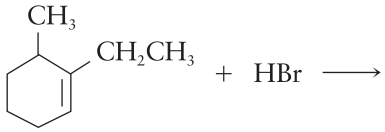


CH$_3$
Cl attaches here
H attaches here
H
CH$_3$
Cl
H
H
or
CH$_3$
Cl

✔ LEARNING CHECK 12.6 Use Markovnikov's rule to predict the major product in the following reactions:

a. 

$\mathrm{CH_3-CH=\overset{CH_3}{\overset{|}{C}}-CH_2-CH_3+HBr}$

b. 

CH$_3$
CH$_2$CH$_3$
+ HBr ⟶

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STUDY TOOLS 12.1

Keeping a Reaction Card File

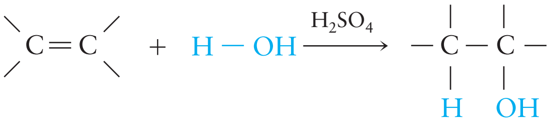
Remembering organic reactions for exams is challenging for most students. Because the number of reactions being studied increases rapidly over the semester, it is a good idea to develop a systematic way to organize them for easy and effective review.

One way to do this is to focus on the functional group concept. When an exam question asks you to complete a reaction by identifying the product, your first step should be to identify the functional group of the reactant. Usually, only the functional group portion of a molecule undergoes reaction. In addition, a particular functional group usually undergoes the same characteristic reactions regardless of the other features of the organic molecule to which it is bound. Thus, by remembering the behavior of a functional group under specific conditions, you can predict the reactions of many compounds, no matter how complex the structures look, as long as they contain the same functional group. For example, any structure containing a C═C will undergo reactions typical of alkenes. Other functional groups will be introduced in later chapters.

Keeping a reaction card file based on the functional group concept is a good way to organize reactions for review. Write the structures and names of the reactants on one side of an index card with an arrow showing any catalyst or special conditions. Write the product structure and name on the back of the card. We recommend that you do this for the general reaction (like those in the Key Reactions section at the end of most chapters) and for a specific example. Review your cards every day (this can even be done while waiting for a bus, etc.), and add to them as new reactions are studied. As an exam approaches, put aside the reactions you know well, and concentrate on the others in what should be a dwindling deck. This is an effective way to focus on learning what you don't know.

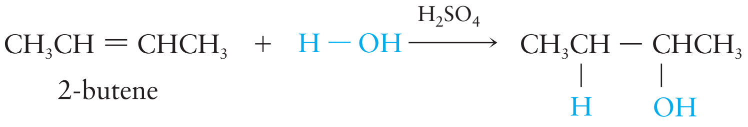
hydration The addition of water to a multiple bond.

In the absence of a catalyst, water does not react with alkenes. But, if an acid catalyst such as sulfuric acid is added, water adds to carbon–carbon double bonds to give alcohols. In this reaction, which is called **hydration**, a water molecule is split in such a way that —H attaches to one carbon of the double bond, and —OH attaches to the other carbon. In Reactions 12.9–12.11, H_2O is written H—OH to emphasize the portions that add to the double bond. Notice that the addition follows Markovnikov's rule:

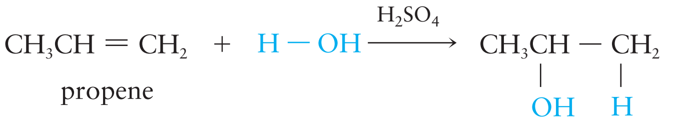


an alcohol

(12.9)

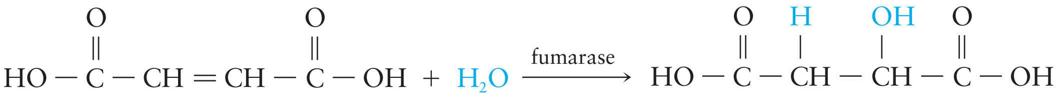


$$\underset{\text{2-butene}}{\mathrm{CH_3CH=CHCH_3}} + \mathrm{H-OH} \xrightarrow{\mathrm{H_2SO_4}} \underset{\text{2-butanol}}{\mathrm{CH_3}\underset{\mathrm{H}}{\underset{|}{\mathrm{CH}}}-\underset{\mathrm{OH}}{\underset{|}{\mathrm{CH}}}\mathrm{CH_3}} \quad (12.10)$$



$$\underset{\text{propene}}{\mathrm{CH_3CH=CH_2}} + \mathrm{H-OH} \xrightarrow{\mathrm{H_2SO_4}} \underset{\text{2-propanol}}{\mathrm{CH_3}\underset{\mathrm{OH}}{\underset{|}{\mathrm{CH}}}-\underset{\mathrm{H}}{\underset{|}{\mathrm{CH_2}}}} \quad (12.11)$$

The hydration of alkenes provides a convenient method for preparing alcohols on a large scale. The reaction is also important in living organisms, but the catalyst is an enzyme rather than sulfuric acid. For example, one of the steps in the body's utilization of carbohydrates for energy involves the hydration of fumaric acid, which is catalyzed by the enzyme fumarase:

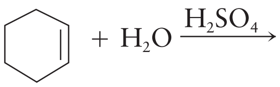


$$\underset{\text{fumaric acid}}{\mathrm{HO}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{CH=CH}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{OH}} + \mathrm{H_2O} \xrightarrow{\text{fumarase}} \underset{\text{malic acid}}{\mathrm{HO}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\overset{\mathrm{H}}{\overset{|}{\mathrm{CH}}}-\overset{\mathrm{OH}}{\overset{|}{\mathrm{CH}}}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{OH}} \quad (12.12)$$

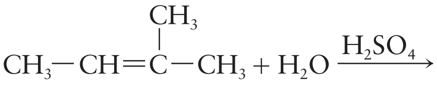
Example 12.7 Writing Hydration Reactions

Hydration is one of the steps in the citric acid cycle (**Section 23.5**). Draw structural formulas for the major organic product of each of the following reactions:

a.



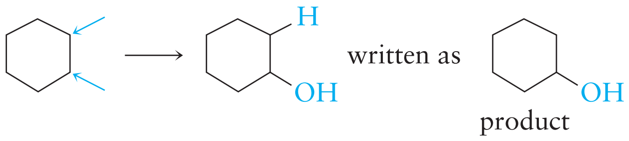
b.



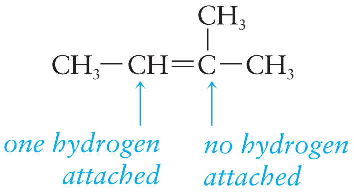
$$CH_3-CH=\overset{CH_3}{\overset{|}{C}}-CH_3 + H_2O \xrightarrow{H_2SO_4}$$

Solution

a. In addition reactions, the carbon–carbon double bond is converted to a single bond. The —H and —OH of water attach to the carbon atoms that were part of the double bond. In the abbreviated product structure, the additional hydrogen atom is not shown; nor are the other hydrogen atoms attached to the ring carbon atoms.

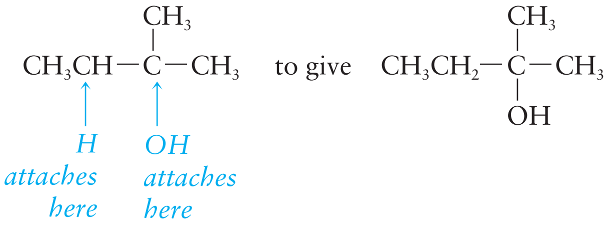


b. With a different number of hydrogen atoms attached to the carbon atoms connected by a double bond, Markovnikov's rule must be followed.



$$CH_3-CH=\overset{CH_3}{\overset{|}{C}}-CH_3$$

The carbon–carbon double bond is converted to a single bond.

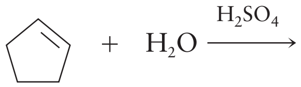


$$CH_3CH-\overset{CH_3}{\overset{|}{C}}-CH_3 \quad \text{to give} \quad CH_3CH_2-\underset{OH}{\underset{|}{\overset{CH_3}{\overset{|}{C}}}}-CH_3$$

✔ **LEARNING CHECK 12.7** Draw structural formulas for the major organic product of each of the following reactions:

a. $CH_3CH_2CH_2CH=CH_2 + H_2O \xrightarrow{H_2SO_4}$

b.



12.4 Addition Polymers

Learning Objective 6 Write equations for addition polymerization, and list uses for addition polymers.

Certain alkenes undergo a very important reaction in the presence of specific catalysts. In this reaction, alkene molecules undergo an addition reaction with one another. The double bonds of the reacting alkenes are converted to single bonds as hundreds or thousands of

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

molecules bond and form long chains. For example, several ethylene molecules react as follows:

$$\underbrace{\mathrm{CH_2{=}CH_2 + CH_2{=}CH_2 + CH_2{=}CH_2 + CH_2{=}CH_2}}_{\text{ethylene molecules}} \xrightarrow[\text{catalysts}]{\text{Heat, pressure,}} \qquad (12.13)$$

$$\underbrace{\mathrm{-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-}}_{\text{polyethylene}}$$

The product is commonly called polyethylene even though there are no longer any double bonds present. The newly formed bonds in this long chain are shown in color. This type of reaction is called a **polymerization**, and the long-chain product made up of repeating units is a **polymer** (*poly* = many, *mer* = parts). The trade names of many polymers such as Orlon, Plexiglas, Lucite, and Teflon are familiar (see **Figure 12.12**). These products are referred to as **addition polymers** because of the addition reaction between double-bonded compounds that is used to produce them. The starting materials that make up the repeating units of polymers are called **monomers** (*mono* = one, *mer* = part). Quite often, common names are used for both the polymer and the monomer. Polymers are used extensively in medicine as suture materials (**Figure 12.13**), tissue adhesives, contact lenses, and vascular grafts.

George Frey/Getty Images

FIGURE 12.12 Gore-Tex is a thin, membranous material made by stretching Teflon fibers. Fabrics layered with Gore-Tex repel wind and rain but allow body perspiration to escape, making it an excellent fabric for sportswear.

polymerization A reaction that produces a polymer.

polymer A very large molecule made up of repeating units.

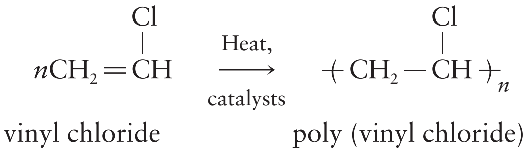
addition polymer A polymer formed by the linking together of many alkene molecules through addition reactions.

monomer The starting material that becomes the repeating units of polymers.

It is not possible to give an exact formula for a polymer produced by a polymerization reaction because the individual polymer molecules vary in size. We could represent polymerization reactions as in Reaction 12.13. However, since this type of reaction is inconvenient, we adopt a commonly used approach: The polymer is represented by a simple repeating unit based on the monomer. For polyethylene, the unit is $\mathrm{+\!(CH_2{-}CH_2)\!+}$. The large number of units making up the polymer is denoted by *n,* a whole number that varies from several hundred to several thousand. The polymerization reaction of ethylene is then written as:

$$\underset{\text{ethylene}}{n\mathrm{CH_2{=}CH_2}} \xrightarrow[\text{catalysts}]{\text{Heat, pressure,}} \underset{\text{polyethylene}}{\mathrm{+\!(CH_2-CH_2)\!+}_n} \qquad (12.14)$$

The lowercase *n* in Reaction 12.14 represents a large, unspecified number. From this reaction, we see that polyethylene is essentially a very long chain alkane. As a result, it has the chemical inertness of alkanes, a characteristic that makes polyethylene suitable for food storage containers, garbage bags, eating utensils, laboratory apparatus, and hospital equipment (see **Figure 12.14**). Polymer characteristics are modified by using alkenes with different groups attached to either or both of the double-bonded carbons. For example, the polymerization of vinyl chloride gives the polymer poly (vinyl chloride), PVC (Reaction 12.15):



$$\underset{\text{vinyl chloride}}{n\mathrm{CH_2{=}\overset{\displaystyle Cl}{\overset{|}{C}}H}} \xrightarrow[\text{catalysts}]{\text{Heat,}} \underset{\text{poly (vinyl chloride)}}{\mathrm{+\!(CH_2-\overset{\displaystyle Cl}{\overset{|}{C}}H)\!+}_n} \qquad (12.15)$$

MedStockPhotos/Alamy Stock Photo

FIGURE 12.13 Sutures composed of synthetic polymers are ideal for soft tissue.

a High-density polyethylene.

b Polystyrene.

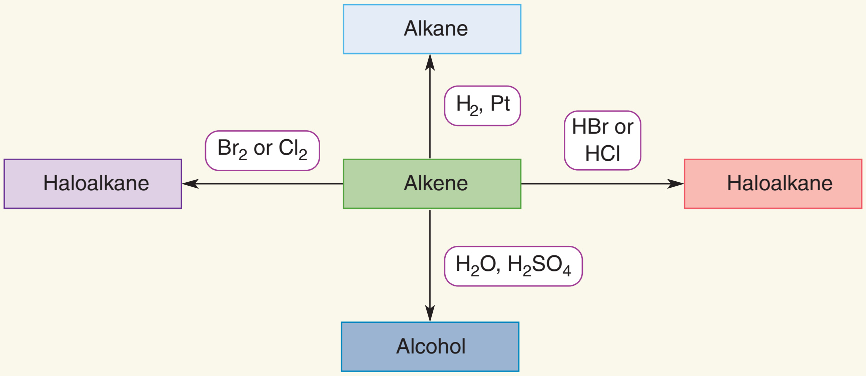
c Polyvinyl chloride.

FIGURE 12.14 Common polymer-based consumer products.

STUDY TOOLS 12.2

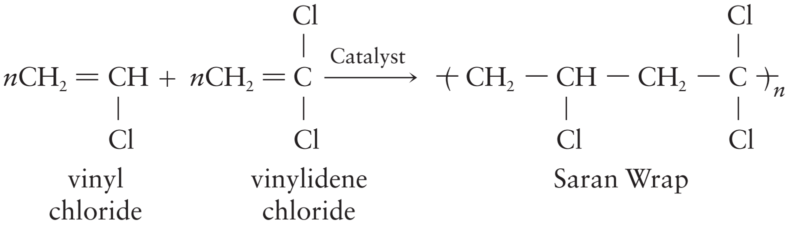
A Reaction Map for Alkenes

A diagram may help you to visualize and remember the four common addition reactions in this section. In each case, the alkene double bond reacts, and an alkane or alkane derivative is produced. The specific reagent determines the outcome of the reaction.



copolymer An addition polymer formed by the reaction of two different monomers.

The commercial product Saran Wrap is an example of a **copolymer**, which is a polymer made up of two different monomers (Reaction 12.16):



$$n\mathrm{CH_2{=}\underset{\underset{\displaystyle Cl}{|}}{CH}} + n\mathrm{CH_2{=}\overset{\overset{\displaystyle Cl}{|}}{\underset{\underset{\displaystyle Cl}{|}}{C}}} \xrightarrow{\text{Catalyst}} \mathrm{+\!\!\left(CH_2{-}\underset{\underset{\displaystyle Cl}{|}}{CH}{-}CH_2{-}\overset{\overset{\displaystyle Cl}{|}}{\underset{\underset{\displaystyle Cl}{|}}{C}} \right)\!\!+_{n}} \qquad (12.16)$$

vinyl chloride — vinylidene chloride — Saran Wrap

A number of the more important addition polymers are shown in **Table 12.3**. As you can tell by looking at some of the typical uses, addition polymers have become nearly indispensable in modern life (see **Figure 12.15**).

aceshot1/Shutterstock.com

Ryan Jorgensen/Jorgo/Shutterstock.com

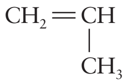
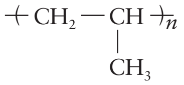
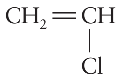
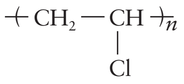
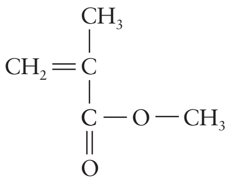
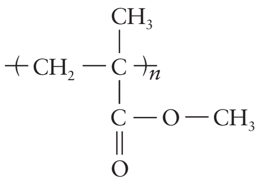
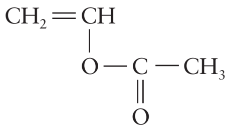
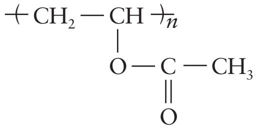
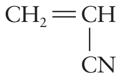
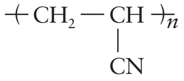
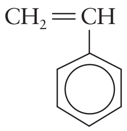
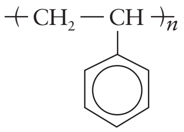
a Automobile safety glass contains a sheet of polyvinyl polymer layered between two sheets of glass to prevent the formation of sharp fragments.

b The elasticity of bubble gum comes from a copolymer of styrene and 1,3-butadiene.

FIGURE 12.15 Two uses of addition polymers. What properties of addition polymers are exhibited in both of these products?

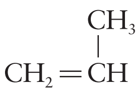
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

TABLE 12.3 Common Addition Polymers

Chemical Name and Trade Name(s)	Monomer	Polymer	Typical Uses
polyethylene	$\mathrm{CH_2=CH_2}$	$+\!\!\left(\mathrm{CH_2-CH_2}\right)\!\!+_n$	Bottles, plastic bags, film
polypropylene	 $\mathrm{\underset{\substack{\vert\\CH_3}}{CH_2=CH}}$	 $+\!\!\left(\mathrm{CH_2-\underset{\substack{\vert\\CH_3}}{CH}}\right)\!\!+_n$	Carpet fiber, pipes, bottles, artificial turf
poly (vinyl chloride) (PVC)	 $\mathrm{CH_2=\underset{\substack{\vert\\Cl}}{CH}}$	 $+\!\!\left(\mathrm{CH_2-\underset{\substack{\vert\\Cl}}{CH}}\right)\!\!+_n$	Synthetic leather, floor tiles, garden hoses, water pipe
polytetrafluoroethylene (Teflon)	$\mathrm{CF_2=CF_2}$	$+\!\!\left(\mathrm{CF_2-CF_2}\right)\!\!+_n$	Pan coatings, plumbers' tape, heart valves, fabrics
poly (methyl methacrylate) (Lucite, Plexiglas)	 $\mathrm{CH_2=\overset{\substack{CH_3\\\vert}}{\underset{\substack{\vert\\C-O-CH_3\\\Vert\\O}}{C}}}$	 $+\!\!\left(\mathrm{CH_2-\overset{\substack{CH_3\\\vert}}{\underset{\substack{\vert\\C-O-CH_3\\\Vert\\O}}{C}}}\right)\!\!+_n$	Airplane windows, paint, contact lenses, fiber optics
poly (vinyl acetate)	 $\mathrm{CH_2=\underset{\substack{\vert\\O-\underset{\substack{\Vert\\O}}{C}-CH_3}}{CH}}$	 $+\!\!\left(\mathrm{CH_2-\underset{\substack{\vert\\O-\underset{\substack{\Vert\\O}}{C}-CH_3}}{CH}}\right)\!\!+_n$	Adhesives, latex paint, chewing gum
polyacrylonitrile (Orlon, Acrilan)	 $\mathrm{CH_2=\underset{\substack{\vert\\CN}}{CH}}$	 $+\!\!\left(\mathrm{CH_2-\underset{\substack{\vert\\CN}}{CH}}\right)\!\!+_n$	Carpets, fabrics
polystyrene (Styrofoam)			Food coolers, drinking cups, insulation

Example 12.8 Drawing Structural Formulas for Addition Polymers

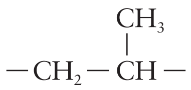
The synthesis of specialty polymers for medical devices is a very active area of science. Draw the structural formula of a portion of polypropylene containing four repeating units of the monomer propylene.



$$\mathrm{CH_2=\overset{\substack{CH_3\\|}}{CH}}$$

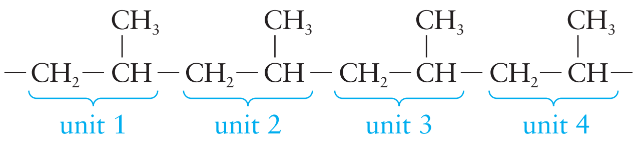
Solution

Remove one of the bonds in the carbon–carbon double bond. Place new bonds on the left and right side of the molecule so that each carbon has four covalent bonds attached.



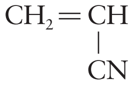
$$\mathrm{-CH_2-\overset{\substack{CH_3\\|}}{CH}-}$$

This is the repeating unit in polypropylene. Now, attach three more units to the structure.



$$-\underbrace{\mathrm{CH_2-\overset{\substack{CH_3\\|}}{CH}}}_{\text{unit 1}}-\underbrace{\mathrm{CH_2-\overset{\substack{CH_3\\|}}{CH}}}_{\text{unit 2}}-\underbrace{\mathrm{CH_2-\overset{\substack{CH_3\\|}}{CH}}}_{\text{unit 3}}-\underbrace{\mathrm{CH_2-\overset{\substack{CH_3\\|}}{CH}}}_{\text{unit 4}}-$$

✔ **LEARNING CHECK 12.8** Draw the structural formula of a portion of polyacrylonitrile containing four repeating units of C_3H_3N as given below:



$$\begin{array}{l} CH_2{=}CH \\ \quad\quad\;\; | \\ \quad\quad\; CN \end{array}$$

12.5 Alkynes

Learning Objective 7 Write the IUPAC names of alkynes from their molecular structures.

ifish/E+/Getty Images

FIGURE 12.16 Alkynes have been isolated from several plant species, marine sponges, and corals.

The characteristic feature of alkynes is the presence of a triple bond between carbon atoms. Thus, alkynes are also unsaturated hydrocarbons. Although relatively rare, compounds containing the carbon–carbon triple bond are found in nature (see **Figure 12.16**). The simplest and most important compound of this series is ethyne, more commonly called acetylene (C_2H_2):

$$H—C{\equiv}C—H$$

acetylene

Acetylene is used in torches for welding steel and in making plastics and synthetic fibers.

Once again, orbital hybridization provides an explanation for the bonding of the carbon atoms. Structurally, the hydrogen and carbon atoms of acetylene molecules lie in a straight line. This same linearity of the triple bond and the two atoms attached to the triple-bonded carbons is found in all alkynes. These characteristics are explained by mixing a 2*s* and a single 2*p* orbital of each carbon to form a pair of *sp* hybrid orbitals. Two of the 2*p* orbitals of each carbon are unhybridized (see **Figures 12.17** and **12.18**).

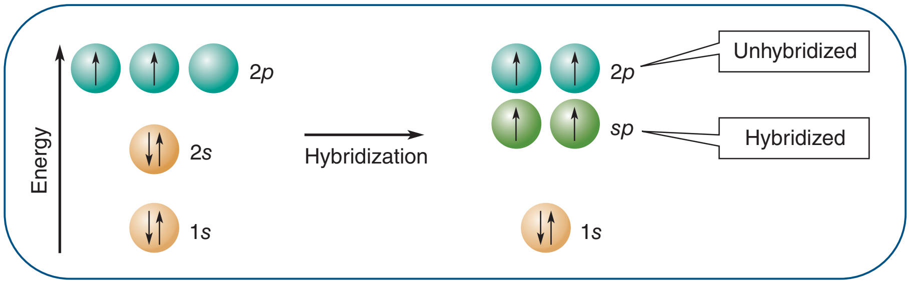


FIGURE 12.17 *sp* hybridization occurs when one of the 2*p* orbitals of carbon mix with the 2*s* orbital. Two 2*p* orbitals remain unhybridized.

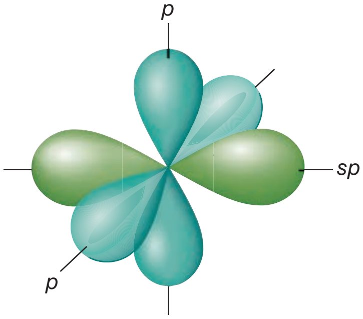
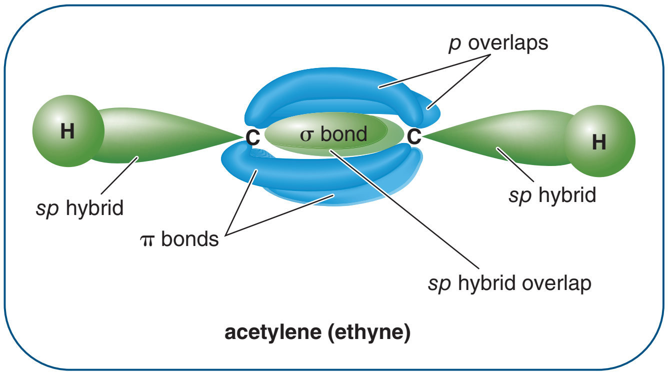


FIGURE 12.18 The unhybridized *p* orbitals are perpendicular to the two *sp* hybridized orbitals.

A carbon–carbon sigma bond in acetylene forms by the overlap of one *sp* hybrid orbital of each carbon. The other *sp* hybrid orbital of each carbon overlaps with a 1*s* orbital of a hydrogen to form a carbon–hydrogen sigma bond. The remaining pair of unhybridized *p* orbitals of each carbon overlap sideways to form a pair of pi bonds between the carbon atoms. Thus, each acetylene molecule contains three sigma bonds (two carbon–hydrogen and one carbon–carbon) and two pi bonds (both are carbon–carbon). This is shown in **Figure 12.19**.

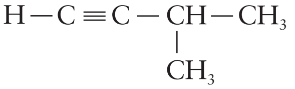
FIGURE 12.19 The shape of acetylene is explained by sigma bonding between *sp* hybrid orbitals and pi bonding between unhybridized *p* orbitals.



Example 12.9 Naming Alkynes

Since the first alkyne was isolated in 1826, well over a thousand alkynes have been discovered in biologically occurring materials, making the naming of alkynes an important skill. Give an IUPAC name for the following alkynes:

a. $CH_3CH_2-C\equiv C-H$

b.

$H-C\equiv C-\underset{\underset{CH_3}{|}}{CH}-CH_3$

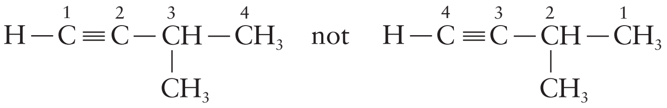
Solution

a. Alkynes are named in exactly the same way as alkenes, except the ending -*yne* is used. The longest chain containing the triple bond has four carbon atoms. The four-carbon alkyne is butyne.

$$\overset{4}{CH_3}\overset{3}{CH_2}-\overset{2}{C}\equiv\overset{1}{C}-H$$

To give lower numbers to the carbons bound by the triple bond, the chain is numbered from the right. The position of the triple bond is indicated by the lower-numbered carbon atom that is triple-bonded, carbon 1 in this case. The name is 1-butyne.

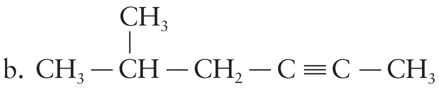
b. To give lower numbers to the carbons bound by the triple bond, the chain is numbered from the left:


$$H-\overset{1}{C}\equiv\overset{2}{C}-\overset{3}{\underset{\underset{CH_3}{|}}{CH}}-\overset{4}{CH_3} \quad \text{not} \quad H-\overset{4}{C}\equiv\overset{3}{C}-\overset{2}{\underset{\underset{CH_3}{|}}{CH}}-\overset{1}{CH_3}$$

Thus, the compound is a 1-butyne with an attached methyl group on carbon 3. Therefore, the name is 3-methyl-1-butyne.

✔ **LEARNING CHECK 12.9** Give the IUPAC name for each of the following:

a. $CH_3-CH_2-C\equiv C-CH_3$

b.

$CH_3-\overset{\overset{CH_3}{|}}{CH}-CH_2-C\equiv C-CH_3$

The physical properties of the alkynes are nearly the same as those of the corresponding alkenes and alkanes. They are insoluble in water, less dense than water, and have relatively low melting and boiling points. Alkynes also resemble alkenes in their addition reactions. The same substances (Br_2, H_2, HCl, etc.) that add to double bonds also add to triple bonds. The one significant difference is that alkynes consume twice as many moles of addition reagent as alkenes in addition reactions that go on to completion.

12.6 Aromatic Compounds and the Benzene Structure

Learning Objective 8 Classify organic compounds as aliphatic or aromatic.

Some of the early researchers in organic chemistry became intrigued by fragrant oils that could be extracted from certain plants. Oil of wintergreen and the flavor component of the vanilla bean (see **Figure 12.20**) are examples. The compounds responsible for the aromas had similar chemical properties. As a result, they were grouped together and called aromatic compounds.

As more and more aromatic compounds were isolated and studied, chemists gradually realized that aromatics contained at least six carbon atoms, had low hydrogen-to-carbon

Owen Franken/Corbis Documentary/ Getty Images

FIGURE 12.20 The coveted culinary spice vanilla comes from the bean of a vining orchid native to Mexico, *Vanilla planifolia*.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

ratios (relative to other organic hydrocarbons), and were related to benzene (C_6H_6). For example, toluene, an aromatic compound extracted the bark of the South American tolu tree, has the formula C_7H_8.

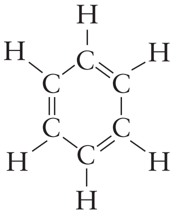
Chemists also learned that the term *aromatic* was not always accurate. Many compounds that belong to the class because of chemical properties and structures are not at all fragrant. Conversely, there are many fragrant compounds that do not have aromatic compound properties or structures. Today, the old class name is used but with a different meaning. Aromatic compounds are those that contain the characteristic benzene ring or its structural relatives. Compounds that do not contain this structure (non-aromatic compounds) are referred to as **aliphatic compounds**. Alkanes, alkenes, and alkynes are, therefore, aliphatic compounds.

aliphatic compound Any organic compound that is not aromatic.

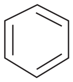
Album/Alamy Stock Photo

FIGURE 12.21 Friedrich August Kekulé (1829–1896).

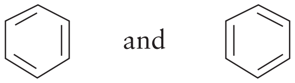
The molecular structure of benzene presented chemists with an intriguing puzzle after the compound was discovered in 1825 by Michael Faraday. The formula C_6H_6 indicated that the molecule was highly unsaturated. However, the compound did not show the typical reactivity of unsaturated hydrocarbons. Benzene underwent relatively few reactions, and these proceeded slowly and often required heat and catalysts. This was in marked contrast to alkenes, which reacted rapidly with many reagents, in some cases almost instantaneously. This apparent discrepancy between structure and reactivity plagued chemists until 1865, when Friedrich August Kekulé (see **Figure 12.21**), a German chemist, suggested that the benzene molecule might be represented by a ring arrangement of carbon atoms with alternating single and double bonds between the carbon atoms:



or



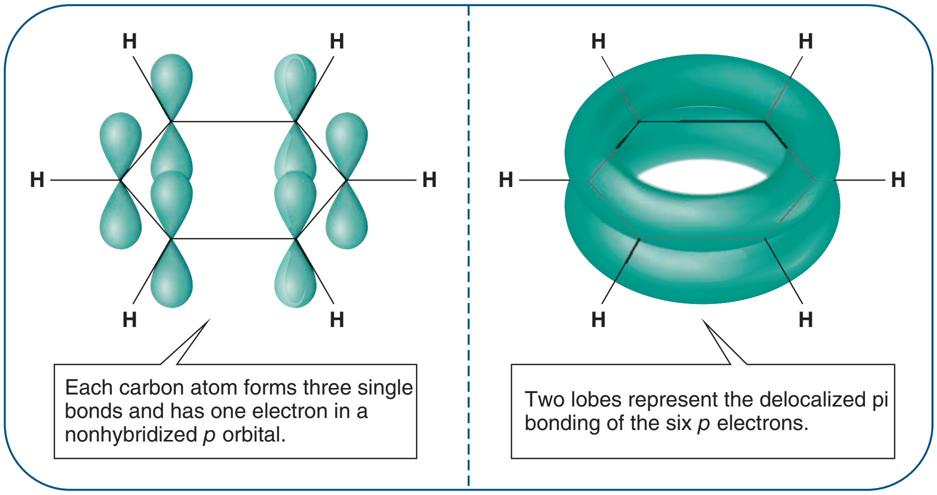
He later suggested that the double bonds alternate in their positions between carbon atoms to give two equivalent structures:



Kekulé structures

A modern interpretation of the benzene structure based on hybridization enables chemists to better understand and explain the chemical properties of benzene and other aromatic compounds. Each carbon atom in a benzene ring has three sp^2 hybrid orbitals and one unhybridized p orbital.

A single sigma bond between carbons of the benzene ring is formed by the overlap of two sp^2 orbitals, one from each of the double-bonded carbons. Because each carbon forms two single bonds, two of the sp^2 hybrid orbitals of each carbon are involved. The third sp^2 hybrid orbital of each carbon forms a single sigma bond with a hydrogen by overlapping with a $1s$ orbital of hydrogen. The unhybridized p orbitals of each carbon overlap sideways above and below the plane of the carbon ring to form two delocalized pi lobes that run completely around the ring in the shape of a double torus. The first torus represents the blended and overlapping orbital area of the six pi lobes that point up, and the torus underneath it represents the blending and overlapping orbital area of the six pi lobes that point down (see **Figure 12.22**).

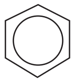


Each carbon atom forms three single bonds and has one electron in a nonhybridized *p* orbital.

Two lobes represent the delocalized pi bonding of the six *p* electrons.

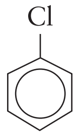
FIGURE 12.22 A hybrid orbital view of the benzene structure.

This interpretation leads to the conclusion that six bonding electrons move freely around the double ring structure formed by the overlapping delocalized pi lobes. Because of this, the benzene structure is often represented by the symbol:

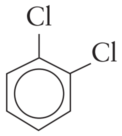


with the circle representing the evenly distributed electrons in the pi lobes. All six carbon and six hydrogen atoms in benzene molecules lie in the same plane (see **Figure 12.22**). Therefore, substituted aromatic compounds do not exhibit *cis-trans* isomerism.

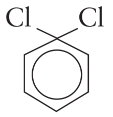
As you draw the structure of aromatic compounds, remember that only one hydrogen atom or group can be attached to a particular position on the benzene ring. For example, compounds (A) and (B) below exist, but (C) does not. Examination of the Kekulé structure of compound (C) shows that the carbon has five bonds attached to it in violation of the octet rule:



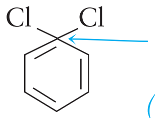
(A)
exists



(B)
exists



(C)
does not
exist



five bonds attached (not possible)

Kekulé
structure

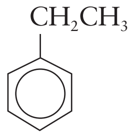
12.7 The Nomenclature of Benzene Derivatives

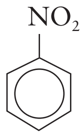
Learning Objective 9 Name and draw structural formulas for aromatic compounds.

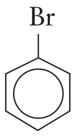
The chemistry of the aromatic compounds developed somewhat haphazardly for many years before systematic nomenclature schemes were developed. Some of the common names used earlier have acquired historical respectability and are used today; some have even been incorporated into the modern systematic nomenclature system.

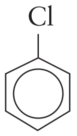
The following guidelines are all based on the IUPAC aromatic nomenclature system. They are not complete, and you will not be able to name all aromatic compounds by using them. However, you will be able to name and recognize those used in this book.

Guideline 1. When a single hydrogen of the benzene ring is replaced, the compound can be named as a derivative of benzene:

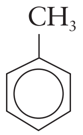

ethylbenzene

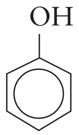

nitrobenzene

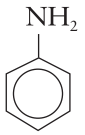

bromobenzene

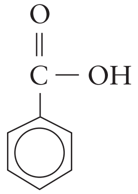

chlorobenzene

Guideline 2. A number of benzene derivatives are known by common names that are also IUPAC-accepted and are used preferentially over other possibilities. Thus, toluene is favored over methylbenzene, and aniline is used rather than aminobenzene:

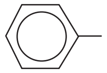

toluene


phenol


aniline

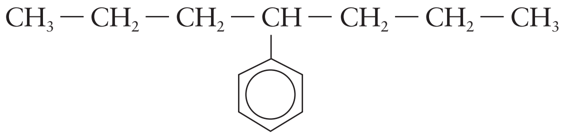

benzoic acid

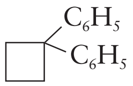
Guideline 3. Compounds formed by replacing a hydrogen of benzene with a more complex hydrocarbon group can be named by designating the benzene ring as the group. This is shown as the benzene ring, $C_6H_5—$,



phenyl group A benzene ring with one hydrogen absent, $C_6H_5—$.

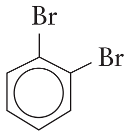
which is also called a **phenyl group**:

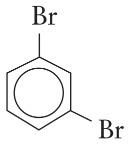

4-phenylheptane

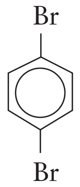

1,1-diphenylcyclobutane

It's easy to confuse the words *phenyl* and *phenol*. The key to keeping them straight is the ending: *-ol* means an alcohol ($C_6H_5—OH$), and *-yl* means a group ($C_6H_5—$).

Guideline 4. When two groups are attached to a benzene ring, three isomeric structures are possible. They can be designated by the prefixes *ortho (o), meta (m),* and *para (p):*


o-dibromobenzene


m-dibromobenzene


p-dibromobenzene

Guideline 5. When two or more groups are attached to a benzene ring, their positions can be indicated by numbering the carbon atoms of the ring so as to obtain the lowest possible numbers for the attachment positions. Groups are arranged in alphabetical order.

HEALTH CONNECTIONS **12.2**

Think before Getting Brown

For many people, well-tanned skin is considered to be very attractive. However, the methods used to achieve this stylish appearance sometimes have some serious health drawbacks.

The body protects itself from ultraviolet (UV) radiation by producing a skin pigment called melanin. The accumulation of melanin in the skin leads to the characteristic tan color and protects the skin from burning and other damage caused by UV radiation. Melanin takes 3 to 5 days to form after initial exposure to the sun. Melanin then helps the skin to gradually tan if the exposure time is kept within reasonable bounds.

Teens are particularly susceptible to the risk of overexposure because they are still experiencing tremendous growth at the cellular level. However, people run the risk of developing skin cancer if they are exposed to the sun or to artificial sunlight in tanning salons too often or for long periods of time.

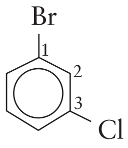
Anyone using the facilities of a tanning salon should find out the recommended exposure times for each bed. At the beginning of developing a tan, an individual should not tan more than every other day. As the tan develops, it is wise to cut back tanning sessions to no more than twice a week. Many salon owners allow individuals to tan for greater periods of time than is safely recommended. Every tanning bed has a chart indicating what frequency and duration are approved by safety standards. If the beds in a salon do not have such charts, the salon is not following safety guidelines, and it would be a good idea to leave.

Exposure to UV rays is known to stimulate addictive behavior that results in increasing tanning frequency and duration. Although a tan is commonly thought to be beautiful, skin cancer certainly is not. Be a conscientious and perceptive consumer.

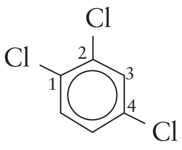
light poet/Shutterstock.com

According to the Food and Drug Administration, the use of artificial tanning devices is not recommended for anyone.

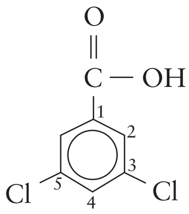
If there is a choice of identical sets of numbers, the group that comes first in alphabetical order is given the lower number. IUPAC-acceptable common names may be used:



m-bromochlorobenzene
or 1-bromo-3-chlorobenzene



1,2,4-trichlorobenzene

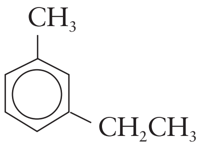


3,5-dichlorobenzoic acid

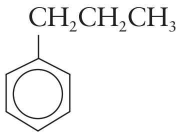
Example 12.10 Naming Aromatic Compounds

Name each of the following aromatic compounds:

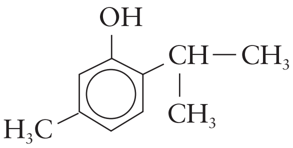
a.



b.



c. Provide the IUPAC name of thymol, an aromatic compound that gives rise to the fragrance of the herb thyme. Its structure is:



Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Solution

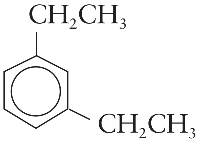
a. This compound is named as a substituted toluene. Both of the following are correct: 3-ethyltoluene and *m*-ethyltoluene. Note that in 3-ethyltoluene the methyl group, which is a part of the toluene structure, must be assigned to position number one.

b. This compound may be named as a substituted benzene or a substituted propane: propylbenzene, 1-phenylpropane.

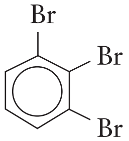
c. This compound is named as a substituted phenol. When three groups are involved, the ring-numbering approach must be used: 2-isopropyl-5-methylphenol.

✔ **LEARNING CHECK 12.10** Name the following aromatic compounds:

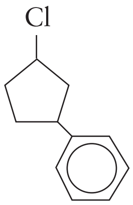
a.



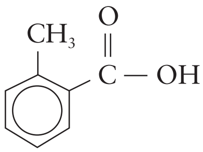
c.



b.



d.



12.8 Properties and Uses of Aromatic Compounds

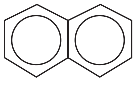
Learning Objective 10 Recognize uses for specific aromatic compounds.

The physical properties of benzene and other aromatic hydrocarbons are similar to those of alkanes and alkenes. They are nonpolar and thus insoluble in water. This hydrophobic characteristic plays an important role in the chemistry of some proteins (see **Chapter 19**).

Aromatic rings are relatively stable chemically. Because of this, benzene often reacts in such a way that the aromatic ring remains intact. Thus, benzene does not undergo the addition reactions that are characteristic of alkenes and alkynes. The predominant type of reaction of aromatic molecules is substitution, in which one of the ring hydrogens is replaced by some other group. Such aromatic reactions are of lesser importance for our purposes and are not shown here.

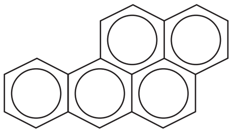
polycyclic aromatic compound A derivative of benzene in which carbon atoms are shared between two or more benzene rings.

All aromatic compounds discussed to this point contain a single benzene ring. There are also substances called **polycyclic aromatic compounds**, which contain two or more benzene rings sharing a common side, or "fused" together. The simplest of these compounds, naphthalene, is the original active ingredient in mothballs:

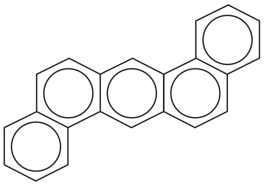


naphthalene

A number of more complex polycyclic aromatic compounds are known to be carcinogens—chemicals that cause cancer. Two of these compounds are:



a benzopyrene



a dibenzanthracene

These cancer-producing compounds are often formed as a result of heating organic materials to high temperatures. They are present in tobacco smoke (see **Figure 12.23**), automobile exhaust, and sometimes in burned or heavily browned food. Such compounds are believed to be at least partially responsible for the high incidence of lung and lip cancer among cigarette smokers. Those who smoke heavily face an increased risk of getting cancer. Chemists have identified more than 4000 compounds in cigarette smoke, including 43 known carcinogens. The Environmental Protection Agency (EPA) considers tobacco smoke a Class A carcinogen.

© Cengage Learning/Charles D. Winters

FIGURE 12.23 Cigarette smoke contains carcinogenic polycyclic aromatic compounds.

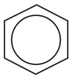
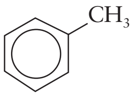
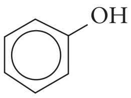
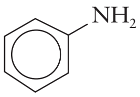
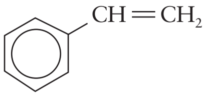
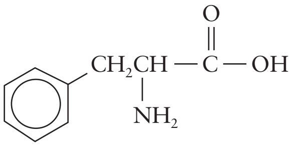
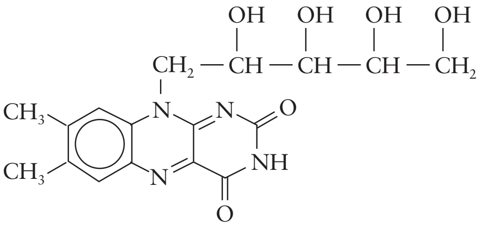
The major sources of aromatic compounds are petroleum and coal tar, a sticky, dark-colored material derived from coal. As with many classes of organic compounds, the simplest structures are the most important commercial materials.

Benzene and toluene are excellent laboratory and industrial solvents. In addition, they are the starting materials for the synthesis of hundreds of other valuable aromatic compounds that are intermediates in the manufacture of a wide variety of commercial products, including the important polymers Bakelite and polystyrene (see **Table 12.4**).

A number of aromatic compounds are important in another respect: They must be present in our diet for proper nutrition. Unlike plants, which have the ability to synthesize the benzene ring from simpler materials, humans must obtain any necessary aromatic rings from their diet. This helps explain why certain amino acids, the building blocks of proteins, and some **vitamins** are dietary essentials (see **Table 12.4**).

vitamin An organic nutrient that the body cannot produce in the small amounts needed for good health.

TABLE 12.4 Some Important Aromatic Compounds

Name	Structural Formula	Use
benzene		Industrial solvent and raw material
toluene		Industrial solvent and raw material
phenol		Manufacture of Bakelite® and Formica®
aniline		Manufacture of drugs and dyes
styrene		Preparation of polystyrene products
phenylalanine		An essential amino acid
riboflavin	 OH OH OH OH CH2—CH—CH—CH—CH2 CH3 CH3 N N N O NH O	Vitamin B_2

Health Career Description

ANESTHESIOLOGIST ASSISTANT

Anesthesiologist assistants work under the direct supervision of an anesthesiologist. They ensure continuity of care by introducing the patient to the anesthesia plan and prepping them for the procedure. Anesthesia assistants are trained in lifesaving skills such as cardiopulmonary resuscitation (CPR). They may work in hospitals or surgical centers. Options are available for typical work hours or on-call and weekend shifts. This career field promises to remain in high demand. Educational requirements include a bachelor's degree in biological or health sciences followed by a 2-year master's degree in anesthesia studies. Anesthesiologist assistants differ from nurse anesthetists in that they do not need to have a nursing license to practice. They take a pre-medical type undergraduate program then move on to an anesthesiology master's degree program.

The website explorehealthcareers.org lists the duties of an anesthesiologist assistant as:

- Taking a complete health history of the patient and performing physical exams to identify any issues that may affect the anesthesia care plan
- Administering necessary diagnostic and laboratory tests (such as taking blood)
- Preparing the patient to be monitored, using non-invasive and invasive methods, as determined by the physician
- Assisting with preparatory procedures, such as pulmonary artery catheterization, electroencephalographic spectral analysis, echocardiography, and evoked potentials
- Pre-testing and calibrating of anesthesia delivery systems and monitors
- Inducing, sustaining, and adjusting anesthesia levels
- Ensuring continuity of care through the postoperative recovery period
- Assisting with life support where required, including airway management
- Performing functions in the intensive care unit and pain clinic
- Performing administrative duties, research and clinical instruction

Anesthesiologist assistants help provide pain-free procedures in hospitals and surgical centers; thereby, providing essential patient care. Because they work with inhaled anesthetics such as nitrous oxide, halothane, isoflurane, desflurane, sevoflurane, in conjunction with oxygen and intravenous anesthetics like midazolam, and propofol, proficiency in chemistry and knowledge of human physiology is critical to success in this field.

Concept Summary

12.1 The Nomenclature of Alkenes

Learning Objective: **Can you classify unsaturated hydrocarbons as alkenes, alkynes, or aromatics? Can you write the IUPAC names of alkenes from their molecular structures?**

- Compounds containing double or triple bonds between carbon atoms are said to be unsaturated.
- The alkenes contain double bonds.
- Alkynes contain triple bonds.
- Aromatics contain a six-member ring with three double bonds.
- In the IUPAC nomenclature system, alkene names end in *-ene*, and alkynes end in *-yne*.

12.2 The Geometry of Alkenes

Learning Objective: **Can you predict the existence of *cis-trans* isomers from formulas of compounds? Can you write the names and structural formulas for *cis-trans* isomers?**

- In alkenes, the double-bonded carbons and the four groups attached to these carbons lie in the same plane.
- Because rotation about the double bond is restricted, alkenes may exist as *cis-trans* isomers.
- This type of stereoisomerism is possible when each double-bonded carbon is attached to two different groups.
- IUPAC names of stereoisomers contain the prefixes *cis-* or *trans-*.

12.3 Properties of Alkenes

Learning Objective: **Can you write equations for addition reactions of alkenes, and use Markovnikov's rule to predict the major products of certain reactions?**

- The physical properties of the alkenes are very similar to those of the alkanes.
- They are nonpolar, insoluble in water, less dense than water, and soluble in nonpolar solvents.
- Alkenes are quite reactive, and their characteristic reaction is addition to the double bond.
- Three important addition reactions are bromination (an example of halogenation) to give a dibrominated alkane, hydration to produce an alcohol, and the reaction with H—X to give an alkyl halide.
- The addition of H_2O and H—X are governed by Markovnikov's rule.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

12.4 Addition Polymers

Learning Objective: Can you write equations for addition polymerization and list uses for addition polymers?

- Addition polymers are formed from alkene monomers that undergo repeated addition reactions with each other.
- Many familiar and widely used materials, such as fibers and plastics, are addition polymers.

12.5 Alkynes

Learning Objective: Can you write the IUPAC names of alkynes from their molecular structures?

- The alkynes contain triple bonds and possess a linear geometry of the two carbons and the two attached groups.
- Alkyne names end in *-yne*.
- The physical and chemical properties of the alkynes are very similar to those of the alkenes.

12.6 Aromatic Compounds and the Benzene Structure

Learning Objective: Can you classify organic compounds as aliphatic or aromatic?

- Benzene, the simplest aromatic compound, and other members of the aromatic class contain a six-membered ring with three double bonds.
- This aromatic ring is often drawn as a hexagon containing a circle, which represents the six electrons of the double bonds that move freely around the ring.
- All organic compounds that do not contain an aromatic ring are called aliphatic compounds.

12.7 The Nomenclature of Benzene Derivatives

Learning Objective: Can you name and draw structural formulas for aromatic compounds?

- Several acceptable IUPAC names are possible for many benzene compounds.
- Some IUPAC names are based on widely used common names such as toluene and aniline.
- Other compounds are named as derivatives of benzene or by designation the benzene ring as a phenyl group.

12.8 Properties and Uses of Aromatic Compounds

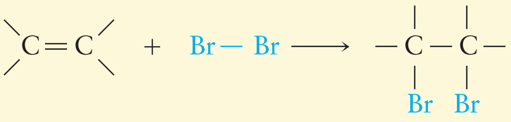
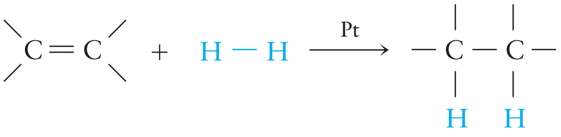
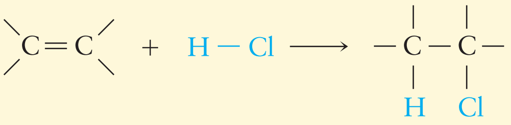
Learning Objective: Can you recognize uses for specific aromatic compounds?

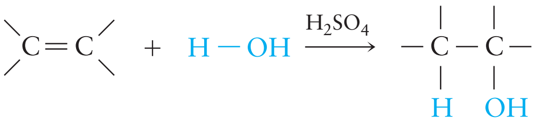
- Aromatic hydrocarbons are nonpolar and have physical properties similar to those of the alkanes and alkenes.
- Benzene resists addition reactions typical of alkenes.
- Benzene and toluene are key industrial chemicals.
- Other important aromatics include phenol, aniline, and styrene.

Key Terms and Concepts

Addition polymer (12.4)
Addition reaction (12.3)
Aliphatic compound (12.6)
Alkene (Introduction)
Alkyne (Introduction)
Aromatic hydrocarbon (Introduction)
Copolymer (12.4)
Haloalkane or alkyl halide (12.3)
Hydration (12.3)
Hydrogenation (12.3)
Markovnikov's rule (12.3)
Monomer (12.4)
Phenyl group (12.7)
Polycyclic aromatic compound (12.8)
Polymer (12.4)
Polymerization (12.4)
Polyunsaturated (12.3)
Unsaturated hydrocarbon (Introduction)
Vitamin (12.8)

Key Equations

1. Halogenation of an alkene (**Section 12.3**):	 $>C{=}C< + Br{-}Br \longrightarrow -\underset{Br}{\underset{\vert}{\overset{\vert}{C}}}-\underset{Br}{\underset{\vert}{\overset{\vert}{C}}}-$	Reaction 12.2
2. Hydrogenation of an alkene (**Section 12.3**):	 $>C{=}C< + H{-}H \xrightarrow{Pt} -\underset{H}{\underset{\vert}{\overset{\vert}{C}}}-\underset{H}{\underset{\vert}{\overset{\vert}{C}}}-$	Reaction 12.4
3. Addition of H—X to an alkene (**Section 12.3**):	 $>C{=}C< + H{-}Cl \longrightarrow -\underset{H}{\underset{\vert}{\overset{\vert}{C}}}-\underset{Cl}{\underset{\vert}{\overset{\vert}{C}}}-$	Reaction 12.6

4. Hydration of an alkene (**Section 12.3**):		Reaction 12.9
5. Addition polymerization of an alkene (**Section 12.4**):	$n\mathrm{CH_2{=}CH_2} \xrightarrow[\text{catalysts}]{\text{Heat, pressure}} \mathrm{+CH_2{-}CH_2+}_n$	Reaction 12.14

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

The Nomenclature of Alkenes (Section 12.1) and Alkynes (Section 12.5)

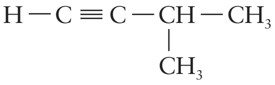
12.1 What is the definition of an *unsaturated hydrocarbon*?

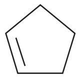
12.2 Define the terms *alkene*, *alkyne*, and *aromatic hydrocarbon*.

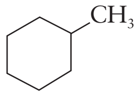
12.3 Select those compounds that can be correctly called *unsaturated* and classify each one as an *alkene* or an *alkyne*:

a. $\mathrm{CH_3{-}CH_2{-}CH_3}$

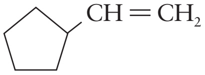
b. $\mathrm{CH_3CH{=}CHCH_3}$

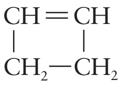
c. 
$\mathrm{H{-}C{\equiv}C{-}\underset{\underset{\displaystyle CH_3}{|}}{CH}{-}CH_3}$

d. 

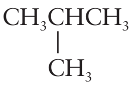
e. 

12.4 Select the compounds that can be correctly called unsaturated and classify each as an alkene or alkyne:

a. 

b. 
$\begin{array}{l}\mathrm{CH{=}CH}\\ \mathrm{|\quad\;\; |}\\ \mathrm{CH_2{-}CH_2}\end{array}$

c. $\mathrm{CH_2{=}CHCH_2CH_3}$

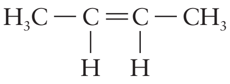
d. 
$\mathrm{CH_3\underset{\underset{\displaystyle CH_3}{|}}{CH}CH_3}$

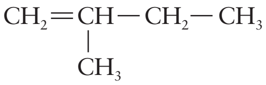
e. $\mathrm{CH_3C{\equiv}CH}$

12.5 Which of the following molecular structures cannot exist in nature? Explain.

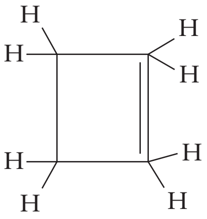
a. $\mathrm{H_2C{=}C{=}CH_2}$

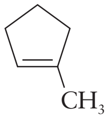
b. $\mathrm{H_3C{-}CH_2{=}CH_3}$

c. 
$\mathrm{H_3C{-}\underset{\underset{\displaystyle H}{|}}{C}{=}\underset{\underset{\displaystyle H}{|}}{C}{-}CH_3}$

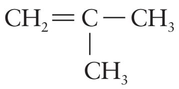
d. 
$\mathrm{CH_2{=}\underset{\underset{\displaystyle CH_3}{|}}{CH}{-}CH_2{-}CH_3}$

12.6 Which of the following molecular structures cannot exist in nature? Explain.

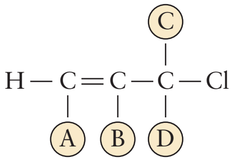
a. 

b. 

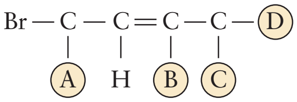
c. $\mathrm{HC{\equiv}C{=}CH_2}$

d. 
$\mathrm{CH_2{=}\underset{\underset{\displaystyle CH_3}{|}}{C}{-}CH_3}$

12.7 The IUPAC name of the compound below is 3,3-dischloro-2,3-difluoro-1-propene. Identify what substituents would be attached at points A, B, C, and D.


$\mathrm{H{-}\underset{\underset{\displaystyle Ⓐ}{|}}{C}{=}\underset{\underset{\displaystyle Ⓑ}{|}}{C}{-}\overset{\overset{\displaystyle Ⓒ}{|}}{\underset{\underset{\displaystyle Ⓓ}{|}}{C}}{-}Cl}$

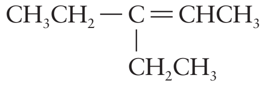
12.8 The IUPAC name of the compound below is 1,1-dibromo-4-methyl-2-pentene. Identify what substituents would be attached at points A, B, C, and D:


$\mathrm{Br{-}\underset{\underset{\displaystyle Ⓐ}{|}}{C}{-}\underset{\underset{\displaystyle H}{|}}{C}{=}\underset{\underset{\displaystyle Ⓑ}{|}}{C}{-}\underset{\underset{\displaystyle Ⓒ}{|}}{C}{-}Ⓓ}$

12.9 Give the IUPAC name for the following compounds:

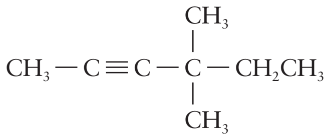
a. $CH_3CH{=}CHCH_3$

b.



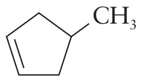
$CH_3CH_2-\underset{\underset{CH_2CH_3}{|}}{C}=CHCH_3$

c.

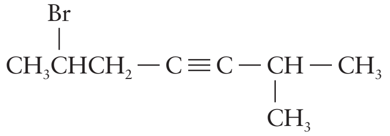


$CH_3-C\equiv C-\overset{\overset{CH_3}{|}}{\underset{\underset{CH_3}{|}}{C}}-CH_2CH_3$

d.

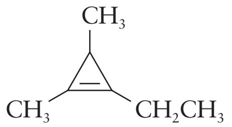


e.

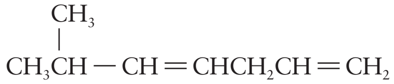


$CH_3\overset{\overset{Br}{|}}{C}HCH_2-C\equiv C-\underset{\underset{CH_3}{|}}{CH}-CH_3$

f.



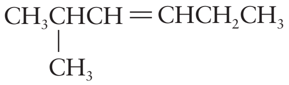
g.



$CH_3\overset{\overset{CH_3}{|}}{C}H-CH=CHCH_2CH=CH_2$

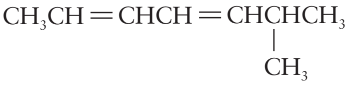
12.10 Give the IUPAC name for the following compounds:

a.



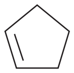
$CH_3\underset{\underset{CH_3}{|}}{C}HCH=CHCH_2CH_3$

b.



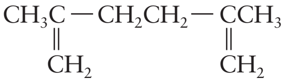
$CH_3CH=CHCH=CH\underset{\underset{CH_3}{|}}{C}HCH_3$

c.



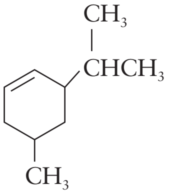
d. $CH_3-C\equiv C-CH_2CH_3$

e.

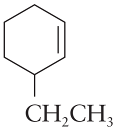


$CH_3\underset{\underset{CH_2}{\|}}{C}-CH_2CH_2-\underset{\underset{CH_2}{\|}}{C}CH_3$

f.



g.



12.11 Give an IUPAC name to each of the hydrocarbons in Problem 12.3.

12.12 Give an IUPAC name to each of the hydrocarbons in Problem 12.4.

12.13 Draw structural formulas for the following compounds:

a. 3-ethyl-2-hexene

b. 3,4-dimethyl-1-pentene

c. 3-methyl-1,3-pentadiene

d. 2-isopropyl-4-methylcyclohexene

e. 1-butylcyclopropene

12.14 Draw structural formulas for the following compounds:

a. 4-methylcyclohexene

b. 2-ethyl-1,4-pentadiene

c. 4,4,5-trimethyl-2-heptyne

d. 4-isopropyl-3,3-dimethyl-1,5-octadiene

e. 2-methyl-1,3-cyclopentadiene

f. 3-*sec*-butyl-3-*t*-butyl-1-heptyne

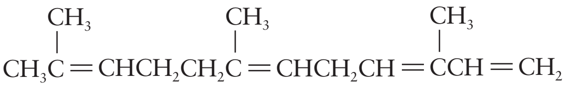
12.15* A compound has the molecular formula C_5H_8. Draw a structural formula for a compound with this formula that would be classified as (a) an alkyne, (b) a diene, and (c) a cyclic alkene. Give the IUPAC name for each compound.

12.16 A compound has the molecular formula C_4H_6. Draw a structural formula for a compound with this formula that would be classified as (a) an alkyne, (b) a diene, and (c) a cyclical alkene. Give the IUPAC name for each compound.

12.17* Draw structural formulas and give IUPAC names for the 13 alkene isomers of C_6H_{12}. Ignore *cis-trans* isomers and cyclic structures.

12.18* Draw structural formulas and give IUPAC name for the five alkene isomers of C_5H_{10}. Ignore *cis-trans* isomers and cyclic structures.

12.19* α-Farnesene is a constituent of the natural wax found on apples. Given that a 12-carbon chain is named as a dodecane, what is the IUPAC name of α-farnesene?



$CH_3\overset{\overset{CH_3}{|}}{C}=CHCH_2CH_2\overset{\overset{CH_3}{|}}{C}=CHCH_2CH=\overset{\overset{CH_3}{|}}{C}CH=CH_2$

α-farnesene

12.20 Each of the following names is wrong. Give the structure and correct name for each compound.

a. 3-pentene

b. 3-methyl-2-butene

c. 2-ethyl-3-pentyne

12.21 Each of the following names is wrong. Give the structure and correct name for each compound.

a. 2-methyl-4-hexene

b. 3,5-heptadiene

c. 4-methylcyclobutene

12.22 Each of the following names is *incorrect*. Determine the correct IUPAC name for each compound.

a. 2-propyl-2-pentene

b. 2,5-dimethyl-5-hexene

c. 2,4-cyclopentadiene

d. 1,1-dimethyl-3-cyclohexene

12.23 Each of the following names is *incorrect*. Determine the correct IUPAC name for each compound.

- **a.** 1,3-dimethyl-3-pentene
- **b.** 5-ethyl-4-hexene
- **c.** 1,1-dimethyl-2,4-cyclohexadiene
- **d.** 1,1,1-trimethyl-3-butene

The Geometry of Alkenes (Section 12.2)

12.24* What type of hybridized orbital is present on carbon atoms bonded by a double bond? How many of these hybrid orbitals are on each carbon atom?

12.25* What type of orbital overlaps to form a pi bond in an alkene? What symbol is used to represent a pi bond? How many electrons are in a pi bond?

12.26 Describe the geometry of the carbon–carbon double bond and the two atoms attached to each of the double-bonded carbon atoms.

12.27 Explain the difference between *cis-trans* and structural isomers of alkenes.

12.28* Draw structural formulas and give IUPAC names for all the isomeric pentenes (C_5H_{10}) that are:

- **a.** Alkenes that do not show *cis-trans* isomerism. There are four compounds.
- **b.** Alkenes that do show *cis-trans* isomerism. There is one *cis* and one *trans* compound.

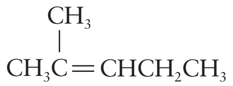
12.29 Draw structural formulas and give IUPAC names for all the isomeric hydrocarbons (C_4H_8) that are:

- **a.** Alkenes that do not show *cis-trans* isomerism. There are two compounds.
- **b.** Alkenes that do show *cis-trans* isomerism. There is one *cis* and one *trans* compound.

12.30 Which of the following alkenes can exist as *cis-trans* isomers? Draw structural formulas and name the *cis* and *trans* isomers.

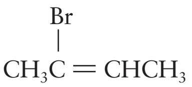
a. $CH_3CH_2CH_2CH_2CH{=}CH_2$

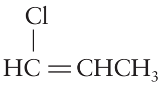
b. $CH_3CH_2CH{=}CHCH_2CH_3$

c.

$CH_3\overset{\overset{CH_3}{|}}{C}{=}CHCH_2CH_3$

12.31 Which of the following alkenes can exist as *cis-trans* isomers? Draw structural formulas and name the *cis* and *trans* isomers.

a. $H_2C{=}CH{-}CH_3$

b.

$CH_3\overset{\overset{Br}{|}}{C}{=}CHCH_3$

c.

$H\overset{\overset{Cl}{|}}{C}{=}CHCH_3$

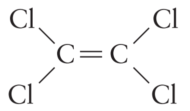
12.32 Draw structural formulas for the following:

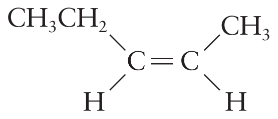
- **a.** *cis*-3-hexene
- **b.** *trans*-3-heptene

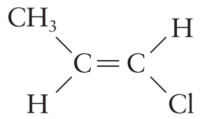
12.33 Draw structural formulas for the following:

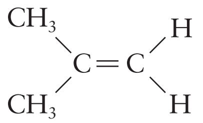
- **a.** *cis*-4-methyl-2-pentene
- **b.** *trans*-5-methyl-2-heptene

12.34 Give an IUPAC name for each of the following molecules. Include the prefix *cis-* or *trans-* when appropriate.

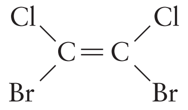
a.


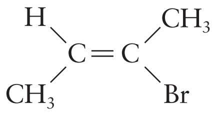
b.


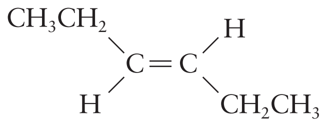
c.


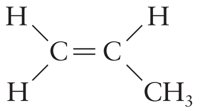
d.


12.35 Give an IUPAC name for each of the following molecules. Include the prefix *cis-* or *trans-* when appropriate.

a.


b.


c.


d.


Properties of Alkenes (Section 12.3)

12.36 In what ways are the physical properties of alkenes similar to those of alkanes?

12.37 Determine whether the following alkenes would be expected to be a solid, a liquid, or a gas at room temperature and pressure.

- **a.** Ethene
- **b.** 2-hexene
- **c.** 3-octene
- **d.** 1,3-cyclohexadiene

12.38 Determine whether each of the following statements is true or false.

- **a.** 2-hexene has a greater density than water.
- **b.** 1-heptene has a higher boiling point than 1-hexene.
- **c.** 2-butene is not flammable.
- **d.** Cyclohexene is a solid at room temperature and pressure.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

12.39 Which of the following reactions is an addition reaction?

a. $C_4H_8 + Cl_2 \rightarrow C_4H_8Cl_2$

b. $C_6H_6 + Cl_2 \rightarrow C_6H_5Cl + HCl$

c. $C_4H_8 + HCl \rightarrow C_4H_9Cl$

d. $C_6H_6 + C_2H_5Cl \rightarrow C_8H_{10} + HCl$

e. $C_7H_{16} \rightarrow C_7H_8 + 4H_2$

12.40 Which of the following reactions is an addition reaction?

a. $A_2 + C_3H_6 \rightarrow C_3H_6A_2$

b. $A_2 + C_6H_6 \rightarrow C_6H_5A + HA$

c. $HA + C_4H_8 \rightarrow C_4H_9A$

d. $3O_2 + C_2H_4 \rightarrow 2CO_2 + 2H_2O$

e. $C_7H_{16} \rightarrow C_7H_8 + 4H_2$

12.41 State Markovnikov's rule, and write a reaction that illustrates its application.

12.42 Write a chemical equation showing reactants, products, and catalysts (if needed) for the reaction of ethene (C_2H_4) with each of the following reactants.

a. Br_2

b. H_2O

c. H_2

d. HI

12.43 Write a chemical equation showing reactants, products, and catalysts (if needed) for the reaction of ethene (C_2H_4) with each of the following reactants.

a. Cl_2

b. H_2O

c. HBr

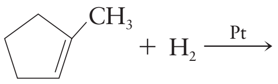
d. I_2

12.44 Write a chemical equation showing reactants, products, and catalysts (if needed for the reaction of 1-butene ($CH_2{=}CHCH_2CH_3$) with each of the reactants in problem 12.42. Use Markovnikov's rule as needed.

12.45 Write a chemical equation showing reactants, products, and catalysts (if needed for the reaction of 1-butene ($CH_2{=}CHCH_2CH_3$) with each of the reactants in problem 12.43. Use Markovnikov's rule as needed.

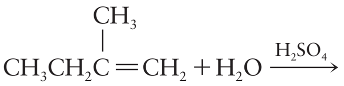
12.46 Complete the following reactions. Where more than one product is possible, show only the one expected according to Markovnikov's rule.

a.



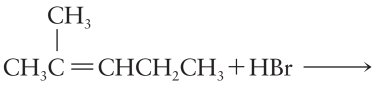
b. $CH_3CH_2CH{=}CH_2 + Cl_2 \longrightarrow$

c.



$CH_3CH_2\overset{CH_3}{C}{=}CH_2 + H_2O \xrightarrow{H_2SO_4}$

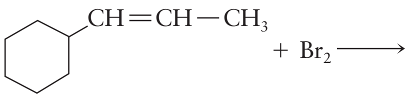
d.



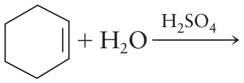
$CH_3\overset{CH_3}{C}{=}CHCH_2CH_3 + HBr \longrightarrow$

12.47 Complete the following reactions. Where more than one product is possible, show only the one expected according to Markovnikov's rule.

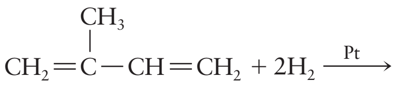
a.



b.

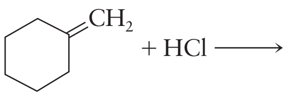


c.



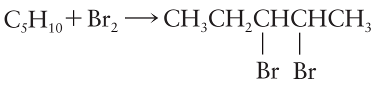
$CH_2{=}\overset{CH_3}{C}-CH{=}CH_2 + 2H_2 \xrightarrow{Pt}$

d.



12.48* Draw the structural formula for the alkenes with molecular formula C_5H_{10} that will react to give the following products. Show all correct structures if more than one starting material will react as shown.

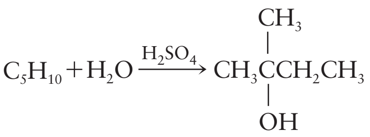
a.



$C_5H_{10} + Br_2 \longrightarrow CH_3CH_2\underset{Br}{CH}\underset{Br}{CH}CH_3$

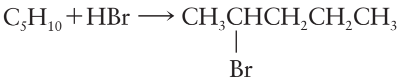
b. $C_5H_{10} + H_2 \xrightarrow{Pt} CH_3CH_2CH_2CH_2CH_3$

c.



$C_5H_{10} + H_2O \xrightarrow{H_2SO_4} CH_3\underset{OH}{\overset{CH_3}{C}}CH_2CH_3$

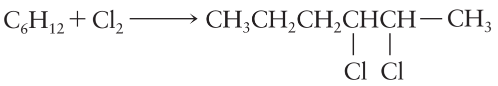
d.



$C_5H_{10} + HBr \longrightarrow CH_3\underset{Br}{CH}CH_2CH_2CH_3$

12.49 Draw the structural formula for the alkenes with molecular formula C_6H_{12} that will react to give the following products. Show all correct structures if more than one starting material will react as shown.

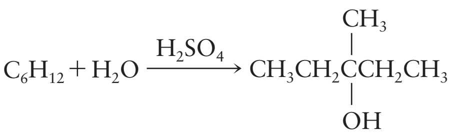
a.



$C_6H_{12} + Cl_2 \longrightarrow CH_3CH_2CH_2\underset{Cl}{CH}\underset{Cl}{CH}-CH_3$

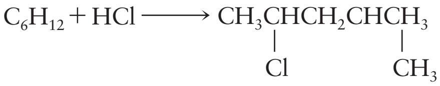
b. $C_6H_{12} + H_2 \xrightarrow{Pt} CH_3CH_2CH_2CH_2CH_2CH_3$

c.



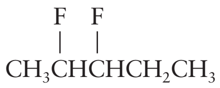
$C_6H_{12} + H_2O \xrightarrow{H_2SO_4} CH_3CH_2\underset{OH}{\overset{CH_3}{C}}CH_2CH_3$

d.

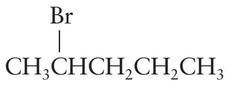


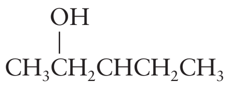
$C_6H_{12} + HCl \longrightarrow CH_3\underset{Cl}{CH}CH_2\underset{CH_3}{CH}CH_3$

12.50* What reagents would you use to prepare each of the following from 2-pentene?

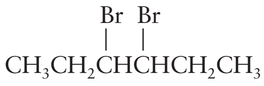
a.

$CH_3\overset{F}{C}H\overset{F}{C}HCH_2CH_3$

b. $CH_3CH_2CH_2CH_2CH_3$

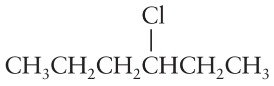
c.

$CH_3\overset{Br}{C}HCH_2CH_2CH_3$

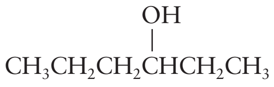
d.

$CH_3CH_2\overset{OH}{C}HCH_2CH_3$

12.51* What reagents would you use to prepare each of the following from 3-hexene?

a.

$CH_3CH_2\overset{Br}{C}H\overset{Br}{C}HCH_2CH_3$

b. $CH_3CH_2CH_2CH_2CH_2CH_3$

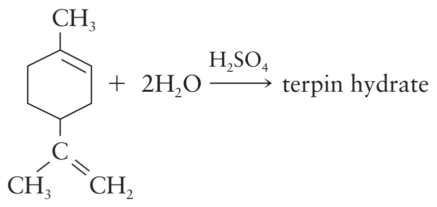
c.

$CH_3CH_2CH_2\overset{Cl}{C}HCH_2CH_3$

d.

$CH_3CH_2CH_2\overset{OH}{C}HCH_2CH_3$

12.52 What is an important commercial application of hydrogenation?

12.53 Cyclohexane and 2-hexene both have the molecular formula C_6H_{12}. Describe a simple chemical test that would distinguish one from the other.

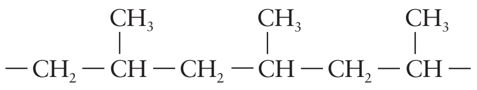
12.54 Terpin hydrate is used medicinally as an expectorant for coughs. It is prepared by the following addition reaction. What is the structure of terpin hydrate?



Addition Polymers (Section 12.4)

12.55 Explain what is meant by each of the following terms: *monomer, polymer, addition polymer,* and *copolymer.*

12.56 A section of polypropylene containing three units of monomer can be shown as:


$-CH_2-\overset{CH_3}{CH}-CH_2-\overset{CH_3}{CH}-CH_2-\overset{CH_3}{CH}-$

Draw structural formulas for comparable three-unit sections of:

a. Teflon

b. Orlon

c. Lucite

12.57 Identify a structural feature characteristic of all monomers listed in **Table 12.3**.

12.58 Draw the "start" (the first three repeating units) of the structural formula of the addition polymers formed from the following monomers.

a. Ethene

b. Chloroethene

c. 1,2-dichloroethene

d. 1,1,2-trichloroethene

12.59 Draw the "start" (the first three repeating units) of the structural formula of the addition polymers formed from the following monomers.

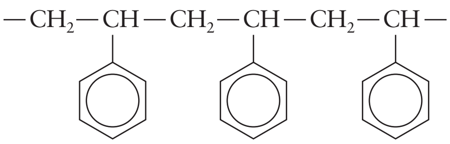
a. Propene

b. 2-mehtyl-1-propene

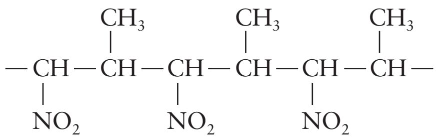
c. 1,1,2,2-tetrafluoroethene

d. 1-butene

12.60 Draw the ethylene derivative (monomer), showing the necessary substituents on the ethylene "backbone," needed to make the following polymer:



12.61 Draw the ethylene derivative (monomer), showing the necessary substituents on the ethylene "backbone," needed to make the following polymer:


$-\underset{NO_2}{CH}-\overset{CH_3}{CH}-\underset{NO_2}{CH}-\overset{CH_3}{CH}-\underset{NO_2}{CH}-\overset{CH_3}{CH}-$

12.62 Rubber cement contains a polymer of 2-methylpropene (isobutylene) called polyisobutylene. Write an equation for the polymerization reaction.

12.63 Much of today's plumbing in newly built homes is made from a plastic called poly (vinyl chloride), or PVC. Using **Table 12.3**, write a reaction for the formation of poly (vinyl chloride).

12.64 Identify a major use for each of the following addition polymers:

a. Styrofoam

b. Acrilan

c. Plexiglas

d. PVC

e. Polypropylene

Alkynes (Section 12.5)

12.65* What type of hybridized orbital is present on carbon atoms bonded by a triple bond? How many of these hybrid orbitals are on each carbon atom?

12.66* How many sigma bonds and how many pi bonds make up the triple bond of an alkyne?

12.67 Describe the geometry in an alkyne of the carbon–carbon triple bond and the two attached atoms.

12.68 Explain why *cis-trans* isomerism is not possible in alkynes.

12.69 Give the common name and major uses of the simplest alkyne.

12.70* Describe the physical and chemical properties of alkynes.

12.71 Write the structural formulas and IUPAC names for all seven isomeric alkynes with the formula C_6H_{10}.

12.72 Write the structural formulas and IUPAC names for all the isomeric alkynes with the formula C_5H_8.

Aromatic Compounds and the Benzene Structure (Section 12.6)

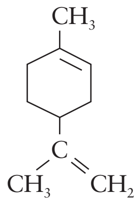
12.73* What type of hybridized orbital is present on the carbon atoms of a benzene ring? How many sigma bonds are formed by each carbon atom in a benzene ring?

12.74* What type of orbital overlaps to form the pi bonding in a benzene ring?

12.75 What does the circle within the hexagon represent in the structural formula for benzene?

12.76 Define the terms *aromatic* and *aliphatic*.

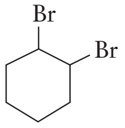
12.77 Limonene, which is present in citrus peelings, has a very pleasant lemonlike fragrance. However, it is not classified as an aromatic compound. Explain.



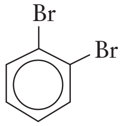
limonene

12.78 A disubstituted cycloalkane such as (a) exhibits *cis-trans* isomerism, whereas a disubstituted benzene (b) does not. Explain.

a.



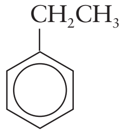
b.



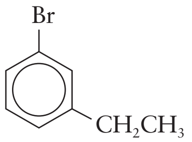
The Nomenclature of Benzene Derivatives (Section 12.7)

12.79 Give an IUPAC name for each of the following hydrocarbons as a derivative of benzene:

a.

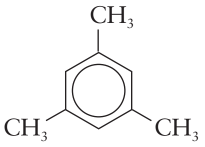


b.

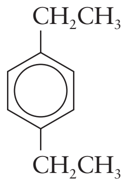


12.80 Give an IUPAC name for each of the following hydrocarbons as a derivative of benzene:

a.

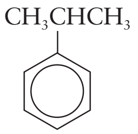


b.

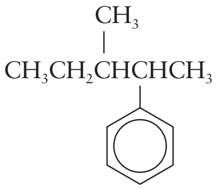


12.81 Give an IUPAC name for the following as hydrocarbons with the benzene ring as a substituent:

a.

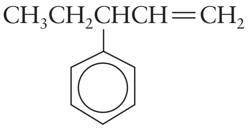


b.



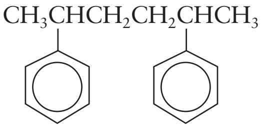
12.82 Give an IUPAC name for the following as hydrocarbons with the benzene ring as a substituent:

a.



$CH_3CH_2CHCH{=}CH_2$

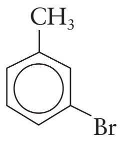
b.



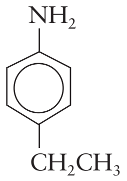
$CH_3CHCH_2CH_2CHCH_3$

12.83 Name the following compounds, using the prefixed abbreviations for *ortho*, *meta*, and *para* and assigning IUPAC-acceptable common names:

a.

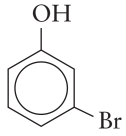


b.

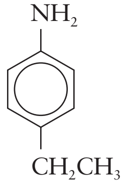


12.84 Name the following compounds, using the prefixed abbreviations for *ortho, meta*, and *para* and assigning IUPAC-acceptable common names:

a.

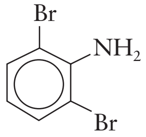


b.

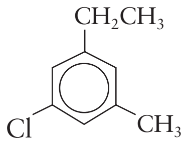


12.85 Name the following by numbering the benzene ring. IUPAC-acceptable common names may be used where appropriate:

a.

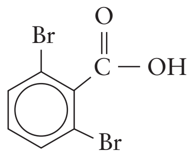


b.

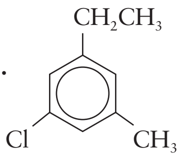


12.86 Name the following by numbering the benzene ring. IUPAC-acceptable common names may be used where appropriate:

a.



b.



12.87 Draw structural formulas for the following:

a. *p*-chloroaniline

b. *m*-ethylphenol

c. 2-phenyl-1-pentene

12.88 Write structural formulas for the following:

a. *o*-ethylphenol

b. *m*-chlorobenzoic acid

c. 3-methyl-3-phenylpentane

12.89 There are three bromonitrobenzene derivatives. Draw their structures and give an IUPAC name for each.

12.90 There are three chlorophenol derivatives. Draw their structures and give an IUPAC name for each one.

Properties and Uses of Aromatic Compounds (Section 12.8)

12.91 Describe the chief physical properties of aromatic hydrocarbons.

12.92 Why does benzene not readily undergo addition reactions characteristic of other unsaturated compounds?

12.93 Compare the chemical behavior of benzene and cyclohexene.

12.94 For each of the following uses, list an appropriate aromatic compound:

a. A solvent

b. A vitamin

c. An essential amino acid

d. Starting material for dyes

12.95 For each of the following uses, list an appropriate aromatic compound:

a. Used in the production of Formica®

b. A starting material for polystyrene

c. Used to manufacture drugs

d. A starting material for Bakelite®

Additional Exercises

12.96 In general, alkynes have slightly higher boiling points and densities than structurally equivalent alkanes. What interparticle force would this be attributable to?

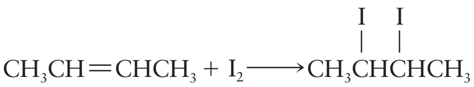
12.97 In Reaction 12.14, heat, pressure, and catalysts are needed to convert ethylene gas to polyethylene. Explain the effects of each of the three conditions (heat, pressure, catalysts) in terms of factors that affect reaction rates.

12.98 Propene reacts with a diatomic molecule whose atoms have the electronic configuration of $1s^22s^22p^63s^23p^5$. Draw the structure of the product formed and give its IUPAC name.

12.99 Draw a generalized energy diagram for the following reaction. Is the reaction endothermic or exothermic?

$$\text{alkene} + \text{water} \xrightarrow{H_2SO_4} \text{alcohol} + 10\ \text{kcal/mol}$$

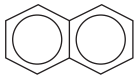
12.100 What will be the limiting reactant when 25.0 g of 2-butene reacts with 25.0 g of iodine to produce 2,3-diiodobutane? How many moles of product could be produced?



$$CH_3CH{=}CHCH_3 + I_2 \longrightarrow CH_3\overset{\displaystyle I}{\overset{|}{C}}H\overset{\displaystyle I}{\overset{|}{C}}HCH_3$$

Chemistry for Thought

12.101 Napthalene is the simplest polycyclic aromatic compound:



Draw a Kekulé structure for this compound like that shown for benzene in **Section 12.6**.

12.102 Why does propene not exhibit *cis-trans* isomerism?

12.103 Limonene is present in the rind of lemons and oranges. Based on its structure (see Exercise 12.77), would you consider it to be a solid, liquid, or gas at room temperature?

12.104 If the average molecular weight of polyethylene is 5.0×10^4 u, how many ethylene monomers ($CH_2{=}CH_2$) are contained in a molecule of the polymer?

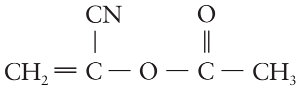
12.105 Reactions to synthesize the benzene ring of aromatic compounds do not occur within the human body, and yet many essential body components involve the benzene structure. How does the human body get its supply of aromatic compounds?

12.106 Answer the question in the caption to **Figure 12.15** pertaining to addition polymers.

12.107 Why can't alkanes undergo addition polymerization?

12.108 Some polymers produce toxic fumes when they are burning. Which polymer in **Table 12.3** produces hydrogen cyanide, HCN? Which produces hydrogen chloride, HCl?

12.109 “Super glue” is an addition polymer of the following monomer. Draw a structural formula for a three-unit section of super glue.



$$\mathrm{CH_2{=}\overset{\overset{\displaystyle CN}{|}}{C}{-}O{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}CH_3}$$

12.110 One of the fragrant components in mint plants is menthene, a compound whose IUPAC name is 1-isopropyl-4-methylcyclohexene. Draw a structural formula for menthene.

13 Alcohols, Phenols, and Ethers

iStock.com/lorenzoantonucci

Health Career Focus

REHABILITATION COUNSELOR/TECHNICIAN

I hit the "snooze" button on my phone for a third time. "The worst part of this job is getting out of bed!" I say as I drag myself out of the covers. I work the night shift at a residential addiction treatment center.

Alcoholism "runs in my family" and I've seen firsthand the many sides of addiction: unemployment, domestic violence, and suicide. Whether they drink or don't drink, everyone in my family is affected; you're either an alcoholic, or you love someone with an alcohol problem.

"Addiction isn't a moral failing. It's physiology, genetics, and chemistry—it's a physical and behavioral issue," I explain to the patients attending my group session. "I'm here to help people find ways to change their behavior so that they and their families can have a better life." Sometimes, people go back to their old habits, but sometimes they break free, and that makes working all night worth it.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Name and draw structural formulas for alcohols and phenols. **(Section 13.1)**
2. Classify alcohols as primary, secondary, or tertiary on the basis of their structural formulas. **(Section 13.2**)
3. Discuss how hydrogen bonding influences the physical properties of alcohols. **(Section 13.3)**
4. Write equations for alcohol dehydration and oxidation reactions. **(Section 13.4)**
5. Recognize uses for specific alcohols. **(Section 13.5)**
6. Recognize uses for specific phenols. **(Section 13.6)**
7. Name and draw structural formulas for ethers. **(Section 13.7)**
8. Describe the key physical and chemical properties of ethers. **(Section 13.8)**
9. Write equations for a thiol reaction with heavy metal ions and the production of disulfides that results when thiols are oxidized. **(Section 13.9)**
10. Identify functional groups in polyfunctional compounds. **(Section 13.10)**

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

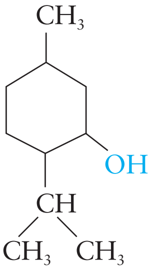
ALCOHOLS, PHENOLS, AND ETHERS are important organic compounds that occur naturally and are produced synthetically in significant amounts. They are used in numerous industrial and pharmaceutical applications (see **Figure 13.1**). Ethanol, for example, is one of the simplest and best known of all organic substances; the fermentation method for producing it was known and used by ancient civilizations. Menthol, a 10-carbon alcohol obtained from peppermint oil, is widely used as a flavoring agent. Cholesterol, with its complicated multi-ring molecular structure, has been implicated in some forms of heart disease. The chemistry of all of these substances is similar because the alcohol functional group behaves essentially the same, regardless of the complexity of the molecule in which it is found.

Inga Spence/Visuals Unlimited/Getty Images

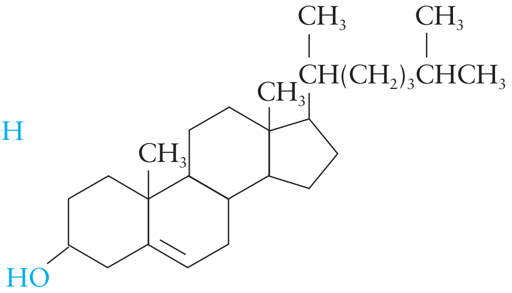
FIGURE 13.1 Taxol, the most commonly used and effective chemotherapy drug for breast cancer, is isolated from the bark of the Pacific yew tree. Though taxol is a complex compound, what does its name suggest about its structure?

CH_3-CH_2-OH

ethanol



menthol



cholesterol

Structurally, an **alcohol** is obtained from a hydrocarbon by replacing a hydrogen atom with a **hydroxy group** (—OH). A formula for an alcohol can be generalized as R — OH, where R— represents CH_3—, CH_3CH_2—, or any other singly bonded carbon–hydrogen group. Thus, R— OH can stand for CH_3 — OH, CH_3CH_2 — OH, and so on. If the replaced hydrogen was attached to an aromatic ring, the resulting compound is known as a **phenol**:

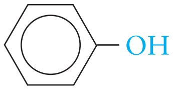
alcohol A compound in which an —OH group is connected to an aliphatic carbon atom.

hydroxy group The —OH functional group.

phenol A compound in which an —OH group is connected to a benzene ring. The parent compound is also called phenol.

$R-OH$

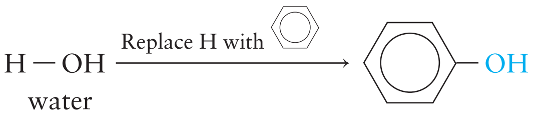
alcohol



phenol

Alcohols and phenols may also be considered to be derived from water by the replacement of one of its hydrogen atoms with an alkyl group or an aromatic ring:

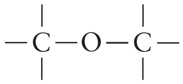
$$\underset{\text{water}}{H-OH} \xrightarrow{\text{Replace H with R}} \underset{\text{alcohol}}{R-OH}$$



water

phenol

ether A compound that contains a



$$-\overset{|}{\underset{|}{C}}-O-\overset{|}{\underset{|}{C}}-$$

functional group.

For most people, the word *ether* generates images of surgeons and operating rooms. Chemists define an **ether** as an organic compound in which two carbon atoms are bonded to an oxygen atom. This structure results when both hydrogen atoms of water are replaced by alkyl groups:

$$\underset{\text{water}}{H-O-H} \xrightarrow{\text{Replace both H's with R}} \underset{\text{ether}}{R-O-R'}$$

R′ indicates that the two R groups can be the same or different.

bogdanhoda/Shutterstock.com

FIGURE 13.2 The word *alcohol* is commonly used to refer to alcoholic drinks, which contain ethyl alcohol. Beer contains ethyl alcohol in the range of 6.1% to 7.6%, depending on the U.S. state in which the brewery is located.

13.1 The Nomenclature of Alcohols and Phenols

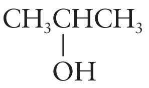
Learning Objective 1 Name and draw structural formulas for alcohols and phenols.

The simpler alcohols are often known by common names, where the alkyl group name is followed by the word *alcohol* (see **Figure 13.2**):

CH_3-OH methyl alcohol

CH_3CH_2-OH ethyl alcohol

$CH_3CH_2CH_2-OH$ propyl alcohol



$$\underset{\underset{OH}{|}}{CH_3CHCH_3}$$

isopropyl alcohol

The IUPAC rules for naming alcohols that contain a single hydroxy group are as follows:

STEP 1. Name the longest chain to which the hydroxy group is attached. The chain name is obtained by dropping the final *-e* from the name of the hydrocarbon that contains the same number of carbon atoms and adding the ending *-ol.*

STEP 2. Number the longest chain to give the lower number to the carbon with the attached hydroxy group.

STEP 3. Locate the position of the hydroxy group by the number of the carbon atom to which it is attached.

STEP 4. Locate and name any branches attached to the chain.

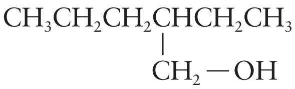
STEP 5. Combine the name and location for other groups, the hydroxy group location, and the longest chain into the final name.

Example 13.1 Naming Alcohols

Name the following alcohols according to the IUPAC system:

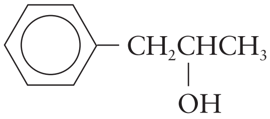
a. CH_3-OH

b.

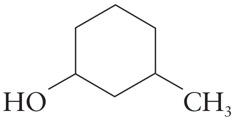


$$CH_3CH_2CH_2\underset{\underset{CH_2-OH}{|}}{C}HCH_2CH_3$$

c.



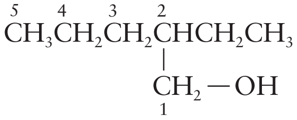
d.



Solution

a. The longest chain has one carbon atom; thus, the alcohol will be called methanol (methane − *e* + *ol*). Since the —OH group can be attached only to the single carbon atom, no location number for —OH is needed.

b. The longest chain containing the —OH group is numbered as follows:



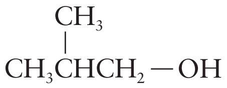
$$\overset{5}{C}H_3\overset{4}{C}H_2\overset{3}{C}H_2\overset{2}{C}HCH_2CH_3 \quad \text{with } \underset{1}{C}H_2-OH \text{ on C2}$$

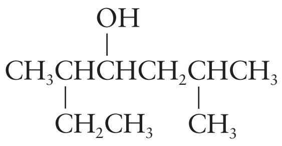
Note that there is a longer chain (six carbon atoms), but the —OH group is not directly attached to it. The five-carbon chain makes the alcohol a pentanol. The —OH group is on carbon number 1; hence, the compound is a 1-pentanol. An ethyl group is attached to carbon number 2 of the chain, so the final name is 2-ethyl-1-pentanol.

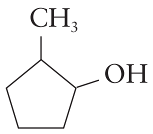
c. The longest chain contains three carbon atoms, with the —OH group attached to carbon number 2. Hence, the compound is a 2-propanol. A benzene ring attached to carbon number 1 is named as a phenyl group. Therefore, the complete name is 1-phenyl-2-propanol. Note that the phenyl group is on carbon number 1 rather than on number 3.

d. The —OH group is given preference, so the carbon to which it is attached is carbon number 1 of the ring. The $-CH_3$ group is located on carbon number 3 (since 3 is lower than 5, which would be obtained by counting the other way). The complete name is 3-methylcyclohexanol. Note that because the —OH group is always at the number-1 position in a ring, the position is not shown in the name.

✔ LEARNING CHECK 13.1 Provide IUPAC names for the following alcohols:

a. 
$CH_3\overset{\displaystyle CH_3}{\overset{|}{C}}HCH_2-OH$

b. 
$CH_3\underset{\underset{\displaystyle CH_2CH_3}{|}}{C}H\overset{\displaystyle OH}{\overset{|}{C}}HCH_2\underset{\underset{\displaystyle CH_3}{|}}{C}HCH_3$

c. 

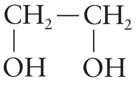
Sebastian Willnow/DDP/Getty Images

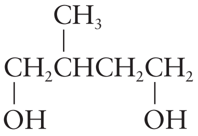
FIGURE 13.3 The diol, ethylene glycol, is used in aircraft de-icers.

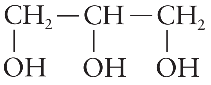
Compounds containing more than one hydroxy group are known. Alcohols containing two hydroxy groups are called *diols* (see **Figure 13.3**). Those containing three —OH groups are called *triols*. The IUPAC nomenclature rules for these compounds are essentially the same as those for the single hydroxy alcohols, except that the ending *-diol* or *-triol* is attached to the name of the parent hydrocarbon.

Example 13.2 More Naming Alcohols

Name the following alcohols according the IUPAC system:

a. 
$\underset{\underset{\displaystyle OH}{|}}{CH_2}-\underset{\underset{\displaystyle OH}{|}}{CH_2}$

b. 
$\underset{\underset{\displaystyle OH}{|}}{CH_2}\overset{\displaystyle CH_3}{\overset{|}{C}}HCH_2\underset{\underset{\displaystyle OH}{|}}{CH_2}$

c. 
$\underset{\underset{\displaystyle OH}{|}}{CH_2}-\underset{\underset{\displaystyle OH}{|}}{CH}-\underset{\underset{\displaystyle OH}{|}}{CH_2}$

(The compound in part c is commonly known as glycerol. It is a component in most cough syrups as a thickening agent, lubricant, and moistening agent.)

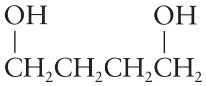
Solution

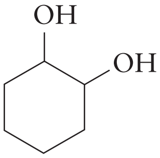
a. The longest chain has two carbons, making this an ethanediol. The —OH groups attached to carbons 1 and 2 give the final name 1,2-ethanediol. This substance is also called ethylene glycol.

b. Because the longest chain has four carbons, the compound is a butanediol. The —OH groups are attached to carbons 1 and 4, and a methyl group is attached to carbon 2. The name is 2-methyl-1,4-butanediol.

c. The longest chain contains three carbons, so the compound is a propanetriol. The —OH groups are attached to carbons 1, 2, and 3, making the name 1,2,3-propanetriol. Common names for this substance are glycerin and glycerol.

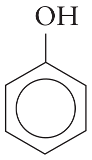
✔ LEARNING CHECK 13.2 Give IUPAC names to the following diols:

a. 
$\overset{\displaystyle OH}{\overset{|}{CH_2}}CH_2CH_2\overset{\displaystyle OH}{\overset{|}{CH_2}}$

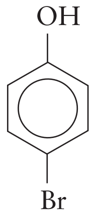
b. 

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

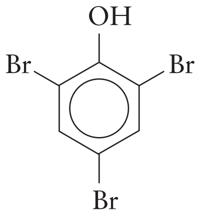
Substituted phenols are usually named as derivatives of the parent compound phenol:



phenol



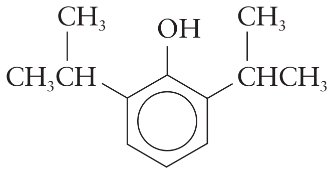
4-bromophenol



2,4,6-tribromophenol

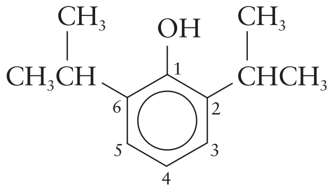
Example 13.3 Naming Phenols

Propofol is an intravenous sedative-hypnotic drug that can be used for the initiation and maintenance of anesthesia. Give an IUPAC name for propofol.



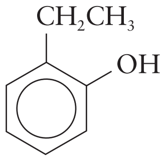
Solution

The presence of the benzene ring with an attached —OH group, designates this compound as a phenol. Assigning position 1 to the ring carbon atom with the —OH attached, gives rise to the following numbers:



The IUPAC name is 2,6-diisopropylphenol.

✔ **LEARNING CHECK 13.3** Name this compound as a phenol:



13.2 Classification of Alcohols

Learning Objective 2 Classify alcohols as primary, secondary, or tertiary on the basis of their structural formulas.

The characteristic chemistry of an alcohol sometimes depends on the groups bonded to the carbon atom that bears the hydroxy group. Alcohols are classified as primary, secondary, or tertiary on the basis of these attached groups (see **Table 13.1**). In a **primary alcohol**, the hydroxy-bearing carbon atom is attached to one other carbon atom and two hydrogen atoms. The simplest alcohol, CH_3—OH, is also considered a primary alcohol. In **secondary alcohol**, the hydroxy-bearing carbon atom is attached to two other carbon atoms and one hydrogen atom. In a **tertiary alcohol**, the hydroxy-bearing carbon atom is attached to three other carbon

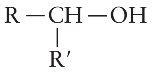
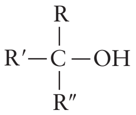
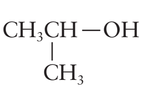
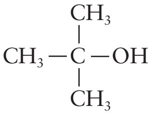
primary alcohol An alcohol in which the OH group is attached to CH_3 or to a carbon attached to one other carbon atom.

secondary alcohol An alcohol in which the carbon bearing the OH group is attached to two other carbon atoms.

tertiary alcohol An alcohol in which the carbon bearing the OH group is attached to three other carbon atoms.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

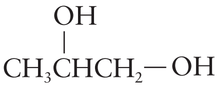
TABLE 13.1 Primary, Secondary, and Tertiary Alcohols

	Primary	Secondary	Tertiary
General formula	$\mathrm{R-CH_2-OH}$	 $\mathrm{R-\underset{\underset{R'}{\vert}}{CH}-OH}$	 $\mathrm{R'-\overset{\overset{R}{\vert}}{\underset{\underset{R''}{\vert}}{C}}-OH}$
Specific example	$\mathrm{CH_3CH_2CH_2-OH}$	 $\mathrm{CH_3\underset{\underset{CH_3}{\vert}}{CH}-OH}$	 $\mathrm{CH_3-\overset{\overset{CH_3}{\vert}}{\underset{\underset{CH_3}{\vert}}{C}}-OH}$
	1-propanol (propyl alcohol)	2-propanol (isopropyl alcohol)	2-methyl-2-propanol (*t*-butyl alcohol)

atoms. The use of R, R′, and R″ in **Table 13.1** signifies that each of those alkyl groups may be different.

Example 13.4 Classification of Alcohols

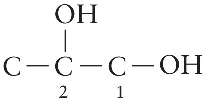
Propylene glycol is used as a solvent in many pharmaceuticals for drugs that are insoluble in water. Classify each of the two hydroxyl groups in propylene glycol as primary, secondary, or tertiary.



$$\mathrm{CH_3\overset{\overset{OH}{|}}{C}HCH_2-OH}$$

Solution

Since classification depends on the number of carbon atoms bonded to the carbon atom that bears the hydroxyl group, look at the carbon skeleton.



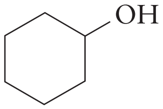
$$\mathrm{C-\overset{\overset{OH}{|}}{\underset{2}{C}}-\underset{1}{C}-OH}$$

Carbon number 1 is bonded to one other carbon atom, which makes the group at position 1 a primary alcohol. The carbon atom at position 2 is bonded to two carbon atoms, making the group at position 2 a secondary alcohol.

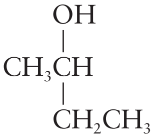
✔ **LEARNING CHECK 13.4** Classify the following alcohols as primary, secondary, or tertiary:

a. $\mathrm{CH_3CH_2CH_2CH_2-OH}$

b.



c.



$$\mathrm{CH_3\overset{\overset{OH}{|}}{\underset{\underset{CH_2CH_3}{|}}{CH}}}$$

13.3 Physical Properties of Alcohols

Learning Objective 3 Discuss how hydrogen bonding influences the physical properties of alcohols.

The replacement of one hydrogen of water with an organic group does not cause all the waterlike properties to disappear. Thus, the lower molecular weight alcohols—methyl, ethyl, propyl, and isopropyl alcohols—are completely miscible with water. As the size of

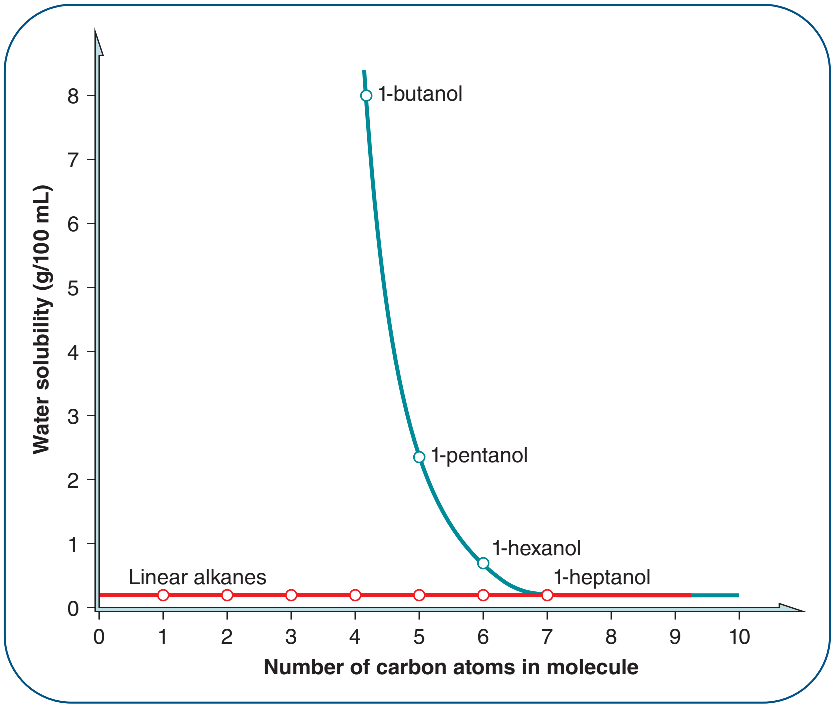
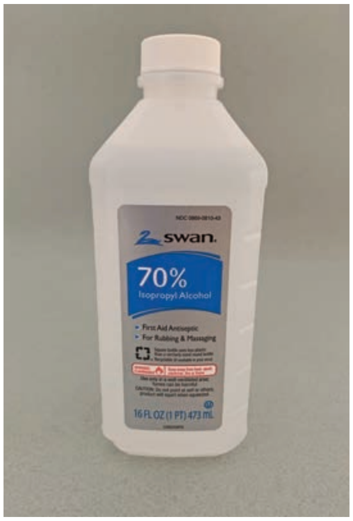


FIGURE 13.4 The solubility of alcohols and linear alkanes in water.



Michael R. Slabaugh

FIGURE 13.5 Isopropyl alcohol, like other low molecular weight alcohols, is highly soluble in water.

the alkyl group in an alcohol increases, the physical properties become less waterlike and more alkanelike. Long-chain alcohols are less soluble in water (see **Figure 13.4**) and more soluble in nonpolar solvents such as benzene, carbon tetrachloride, and ether. The solubility of alcohols in water depends on the number of carbon atoms per hydroxy group in the molecule. In general, one hydroxy group can solubilize three to four carbon atoms. The high solubility of the lower molecular weight alcohols in water (see **Figure 13.5**) can be attributed to hydrogen bonding between the alcohol and water molecules (see **Figure 13.6**).

In long-chain alcohols, the hydrophobic alkyl group does not form hydrogen bonds with water. Thus, in 1-heptanol, water molecules surround and form bonds with the —OH end but do not bond to the alkyl portion (see **Figure 13.7**). Because the alkyl portion is unsolvated, 1-heptanol is insoluble in water. Its solubility in water is comparable to that of heptane (seven carbon atoms), as shown in **Figure 13.4**.

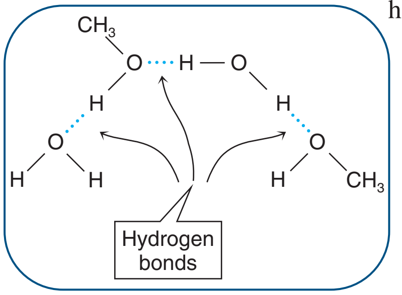


FIGURE 13.6 Hydrogen bonding in a water–methanol solution. A three-dimensional network of molecules and hydrogen bonds is formed.

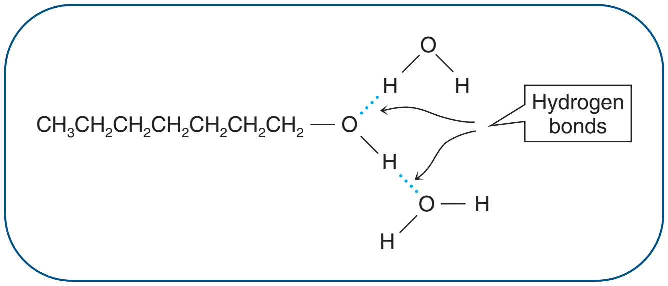


FIGURE 13.7 Water interacts only with the —OH group of 1-heptanol.

✔ **LEARNING CHECK 13.5** Arrange the following compounds in order of increasing solubility in water (least soluble first, most soluble last):

a. $CH_3CH_2CH_2$—OH
b. $CH_3CH_2CH_3$
c. $CH_3(CH_2)_3CH_2$—OH

Hydrogen bonding also causes alcohols to have much higher boiling points than most other compounds of similar molecular weight. In this case, the hydrogen bonding is between alcohol molecules (see **Figure 13.8**). Ethanol (CH_3CH_2OH) boils at 78°C, whereas methyl ether ($CH_3—O—CH_3$) (with the same molecular weight) boils at −24°C. Propane ($CH_3CH_2CH_3$) has nearly the same molecular weight but boils at −42°C (see **Figure 13.9**).

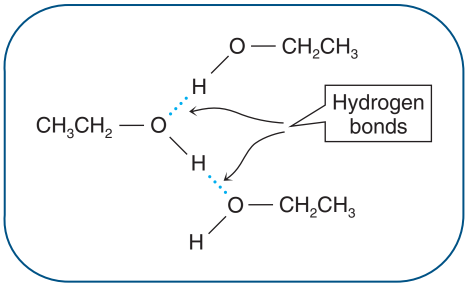


FIGURE 13.8 Hydrogen bonding in pure ethanol.

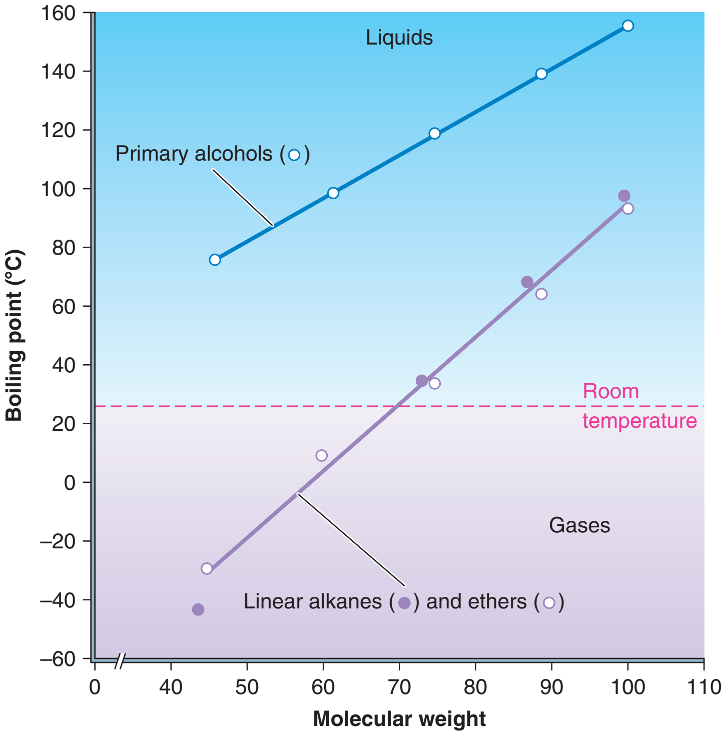


FIGURE 13.9 The boiling points of alcohols are higher than those of alkanes and ethers of similar molecular weights.

> ✔ **LEARNING CHECK 13.6** How can you explain the observation that methanol has a boiling point of 65°C, whereas propane, with a higher molecular weight, has a boiling point of −42°C?

13.4 Reactions of Alcohols

Learning Objective 4 Write equations for alcohol dehydration and oxidation reactions.

Alcohols undergo many reactions, but we will consider only two important ones at this time—alcohol dehydration and alcohol oxidation. In an alcohol **dehydration reaction**, water is chemically removed from an alcohol. This reaction can occur in two different ways, depending on the reaction temperature. At 140°C, the main product is an ether, whereas at higher temperatures (180°C), alkenes are the predominant products.

dehydration reaction A reaction in which water is chemically removed from a compound.

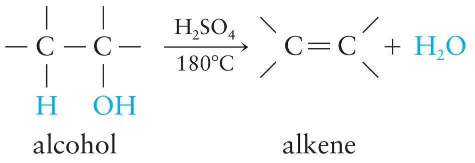
13.4A Dehydration to Produce an Alkene

When the elements of a water molecule are removed from a single alcohol molecule, an alkene is produced. A reaction of this type, in which two or more covalent bonds are broken and a new multiple bond is formed, is called an **elimination reaction**. In this case, a water molecule is eliminated from an alcohol. Reaction 13.1 gives a general reaction, and Reactions 13.2 and 13.3 are two specific examples:

elimination reaction A reaction in which two or more covalent bonds are broken and a new multiple bond is formed.

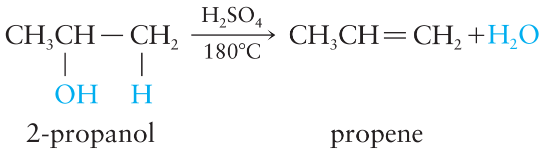
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

General reaction:



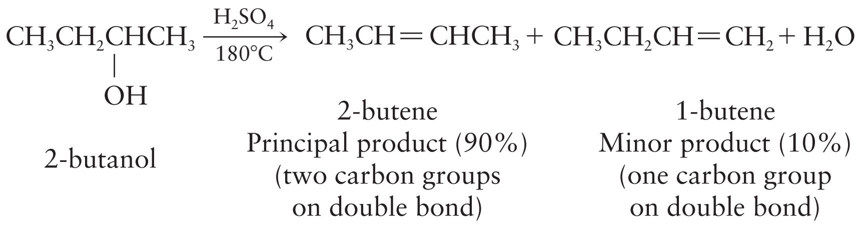
(13.1)

Specific example:



$$\underset{\text{2-propanol}}{CH_3\underset{|}{\overset{}{C}}H(OH)-CH_2(H)} \xrightarrow[180^\circ C]{H_2SO_4} \underset{\text{propene}}{CH_3CH=CH_2} + H_2O \qquad (13.2)$$

Specific example:



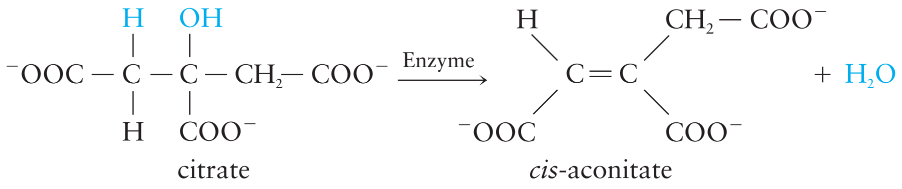
$$\underset{\text{2-butanol}}{CH_3CH_2CH(OH)CH_3} \xrightarrow[180^\circ C]{H_2SO_4} CH_3CH=CHCH_3 + CH_3CH_2CH=CH_2 + H_2O \qquad (13.3)$$

2-butene
Principal product (90%)
(two carbon groups
on double bond)

1-butene
Minor product (10%)
(one carbon group
on double bond)

Notice that in Reaction 13.3 two alkenes can be produced, depending on which carbon next to the hydroxy-bearing carbon loses the hydrogen atom. The principal alkene produced in such cases will be the one in which the higher number of carbon groups is bonded to the double-bonded carbon atoms.

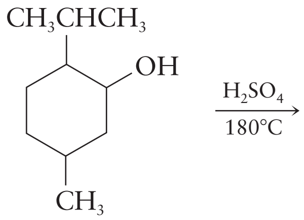
Alcohol dehydration is an important reaction in the human body, where enzymes (rather than sulfuric acid) function as catalysts. For example, the dehydration of citrate is part of the citric acid cycle discussed in **Section 23.5**. Note that the dehydration of citrate, 2-propanol (Reaction 13.2), and 2-butanol (Reaction 13.3) all involve exactly the same changes in bonding. In each reaction, an H and an —OH are removed from adjacent carbons, leaving a C=C double bond. The other molecular bonds in all three of those compounds do not change:



(13.4)

Example 13.5 Dehydration of an Alcohol

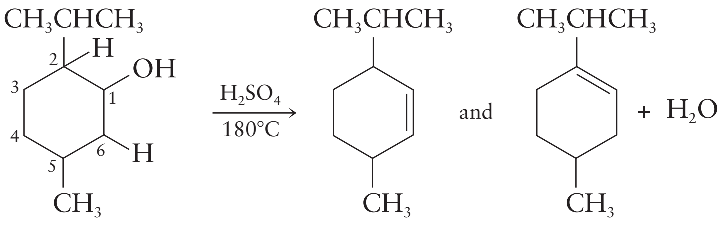
Menthol is a component of ointments, like Vicks VapoRub, which are used to ease minor muscle aches. Predict the major product of the following reaction of menthol:



Solution

This reaction is similar to Key Reaction 13.1, where a molecule of water is removed and an alkene forms. The —OH group is removed along with a —H atom from an adjacent carbon atom (not the carbon to which the —OH is attached). There are —H atoms on both adjacent carbons (2 and 6).

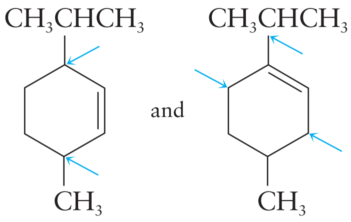
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.



a. b.

If the water molecule removed involves the -OH (position 1) and -H (position 6), product a is formed. If the formation of water involves the —OH (position 1) and —H (position 2), product b is formed.

The major product is the one which has the higher number of carbon atoms bonded to the carbons of the double bond. Arrows point to each of those carbons bonded to C=C.

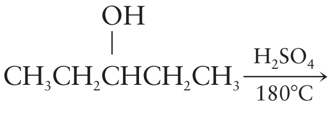


a. b.

Structure b has more arrows and is the major product.

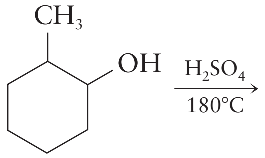
✔ LEARNING CHECK 13.7 Predict the major products of the following reactions:

a.



$$CH_3CH_2\overset{\overset{\Large OH}{|}}{C}HCH_2CH_3 \xrightarrow[180°C]{H_2SO_4}$$

b.



13.4B Dehydration to Produce an Ether

Alcohol dehydration can also occur when the elements of water are removed from two alcohol molecules. The residual molecular fragments of the alcohols bond and form an ether. This ether-forming reaction is useful mainly with primary alcohols. Reaction 13.5 gives the general reaction, and the formation of diethyl ether (the anesthetic ether) is a specific example (Reaction 13.6). Diethyl ether is no longer used as an inhalation anesthetic because of its flammability.

General reaction:

$$\underset{\text{alcohol}}{R-O-H} + \underset{\text{alcohol}}{H-O-R} \xrightarrow[140°C]{H_2SO_4} \underset{\text{ether}}{R-O-R} + H_2O \qquad (13.5)$$

Specific example:

$$\underset{\substack{\text{ethanol}\\\text{(ethyl alcohol)}}}{CH_3CH_2-OH} + \underset{\substack{\text{ethanol}\\\text{(ethyl alcohol)}}}{HO-CH_2CH_3} \xrightarrow[140°C]{H_2SO_4} \underset{\text{diethyl ether}}{CH_3CH_2-O-CH_2CH_3} + H_2O \qquad (13.6)$$

Thus, an alcohol can be dehydrated to produce either an alkene or an ether. The type of dehydration that takes place is controlled by the temperature, with sulfuric acid serving as a catalyst.

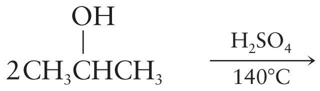
Although a mixture of alkene and ether products often results, we will use these temperatures to indicate that the major dehydration product is an alkene (at 180°C) or an ether (at 140°C).

The reaction that produces ethers is an example of a dehydration synthesis in which two molecules are joined and a new functional group is generated by the removal of a water molecule. Dehydration synthesis is important in living organisms because it is part of the formation of carbohydrates, fats, proteins, and many other essential substances.

Example 13.6 More Alcohol Dehydration

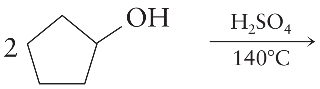
Predict the major products of the following reactions:

a.



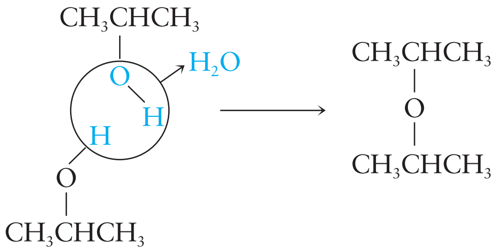
$$2\,CH_3\overset{\overset{\textstyle OH}{|}}{C}HCH_3 \xrightarrow[140°C]{H_2SO_4}$$

b.

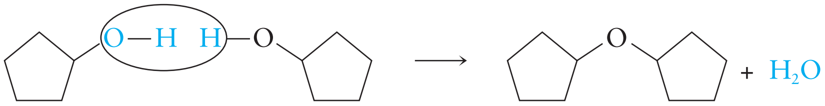


Solution

a. This reaction is similar to Key Reaction 13.5, where two molecules of alcohol come together to form an ether.



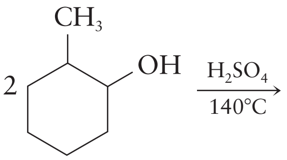
b. Again, this reaction is similar to Key Reaction 13.5, so two molecules of alcohol will come together to form an ether.



✔ LEARNING CHECK 13.8 Predict the major products of the following reactions:

a. $2CH_3CH_2CH_2—OH \xrightarrow[140°C]{H_2SO_4}$

b.

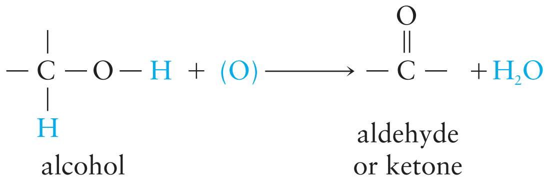


ASP/YPP/INSADCO Photography/ Alamy Stock Photo

FIGURE 13.10 The Breathalyzer test is based upon the oxidation of ethanol in a person's breath. Blood alcohol level is related to the concentration of alcohol in the breath.

13.4C Oxidation

An oxidation reaction occurs when a molecule gains oxygen atoms or loses hydrogen atoms. Under appropriate conditions, alcohols can be oxidized (see **Figure 13.10**) in a controlled way (not combusted) by removing two hydrogen atoms per molecule. A number of oxidizing agents can be used, including potassium dichromate ($K_2Cr_2O_7$) and potassium permanganate ($KMnO_4$). The symbol (O) is used to represent an oxidizing agent. Reaction 13.7 gives the general reaction:

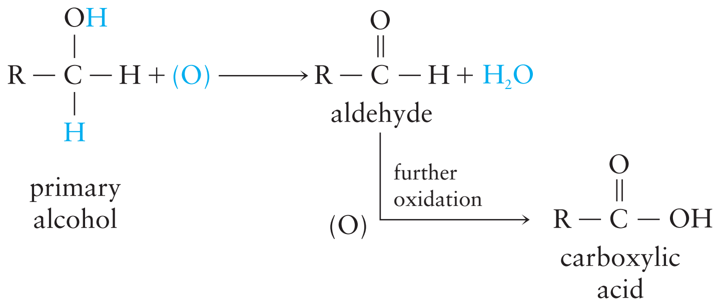


$$\underset{\text{alcohol}}{-\overset{|}{\underset{\underset{H}{|}}{C}}-O-H} + (O) \longrightarrow \underset{\text{aldehyde or ketone}}{-\overset{\overset{O}{\|}}{C}-} + H_2O \qquad (13.7)$$

The three classes of alcohols behave differently toward oxidizing agents.

Primary Alcohols. Reaction 13.8 gives the general reaction, and the formation of acetic acid is a specific example (Reaction 13.9):

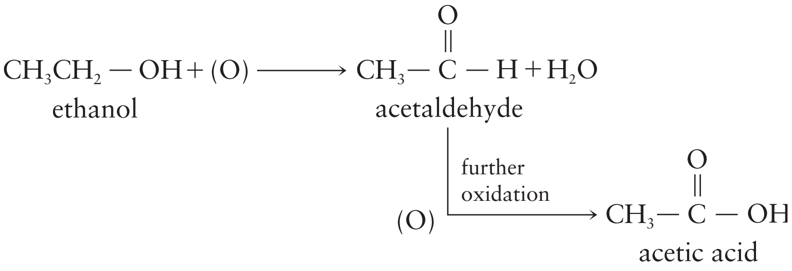
General reaction:



$$\underset{\text{primary alcohol}}{R-\overset{\overset{OH}{|}}{\underset{\underset{H}{|}}{C}}-H} + (O) \longrightarrow \underset{\text{aldehyde}}{R-\overset{\overset{O}{\|}}{C}-H} + H_2O \qquad (13.8)$$

$$\text{aldehyde} \xrightarrow[\text{further oxidation}]{(O)} \underset{\text{carboxylic acid}}{R-\overset{\overset{O}{\|}}{C}-OH}$$

Specific example:



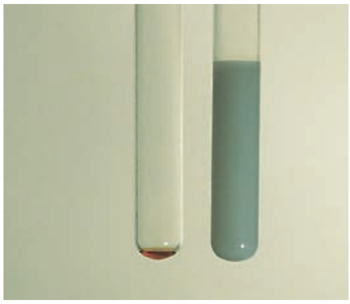
$$\underset{\text{ethanol}}{CH_3CH_2-OH} + (O) \longrightarrow \underset{\text{acetaldehyde}}{CH_3-\overset{\overset{O}{\|}}{C}-H} + H_2O \qquad (13.9)$$

$$\text{acetaldehyde} \xrightarrow[\text{further oxidation}]{(O)} \underset{\text{acetic acid}}{CH_3-\overset{\overset{O}{\|}}{C}-OH}$$

The immediate product of the oxidation of a primary alcohol is an aldehyde. However, aldehydes are readily oxidized by the same oxidizing agents (see **Section 14.3**) to give carboxylic acids. Therefore, the oxidation of a primary alcohol normally results in the corresponding carboxylic acid as the product. The oxidation of ethanol by $K_2Cr_2O_7$ is shown in **Figure 13.11**. Because aldehydes do not hydrogen bond (see **Section 14.2**), they have lower boiling points than the corresponding alcohol or carboxylic acid. This makes it possible to isolate the aldehyde product before it is oxidized by maintaining the reaction temperature high enough to boil the aldehyde out of the reaction mixture before it can react.

© Spencer L. Seager

1 The tube on the left contains orange $K_2Cr_2O_7$ and is next to the colorless ethanol.



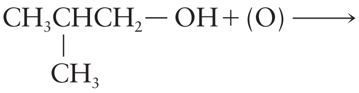
© Spencer L. Seager

2 After mixing, the ethanol is oxidized, and chromium is reduced, forming a grayish-green precipitate.

FIGURE 13.11 Oxidation of ethanol by $K_2Cr_2O_7$. How might a color change like this one be used to measure alcohol concentration?

Example 13.7 Oxidation Reactions

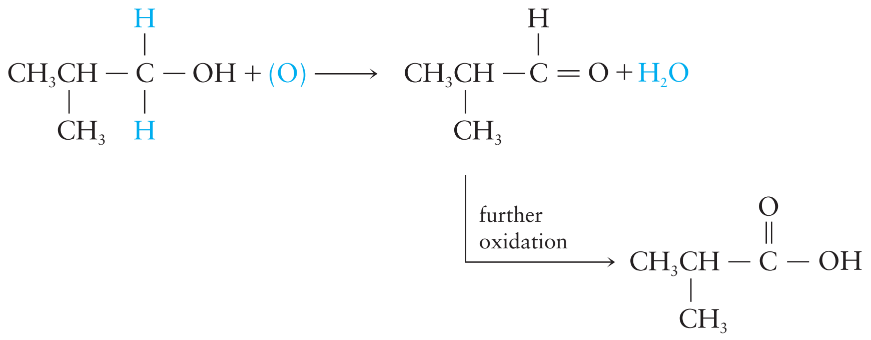
Draw the structural formulas for the first and second products of the following reaction:



$$\underset{\underset{CH_3}{|}}{CH_3CH}CH_2-OH + (O) \longrightarrow$$

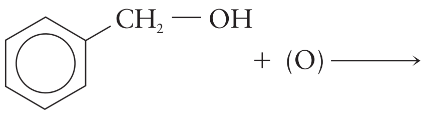
Solution

This reaction is similar to Key Reaction 13.8, where a primary alcohol is first oxidized to an aldehyde and then to a carboxylic acid.



$$\underset{\displaystyle CH_3}{CH_3\underset{|}{CH}}-\overset{\displaystyle H}{\underset{\displaystyle H}{C}}-OH+(O)\longrightarrow \underset{\displaystyle CH_3}{CH_3\underset{|}{CH}}-\overset{\displaystyle H}{C}=O+H_2O$$

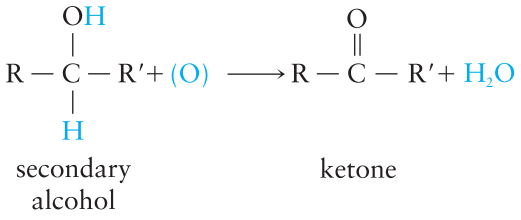
$$\xrightarrow{\text{further oxidation}} \underset{\displaystyle CH_3}{CH_3\underset{|}{CH}}-\overset{\displaystyle O}{\overset{\|}{C}}-OH$$

> ✔ **LEARNING CHECK 13.9** Draw the structural formulas of the first and second products of the following reaction:
>
> 

Secondary Alcohols.

Reactions 13.10 and 13.11 give the general reaction and a specific example.

General reaction:

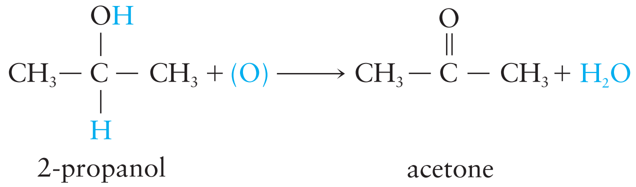


$$R-\overset{\displaystyle OH}{\underset{\displaystyle H}{C}}-R'+(O)\longrightarrow R-\overset{\displaystyle O}{\overset{\|}{C}}-R'+H_2O \qquad (13.10)$$

secondary alcohol

ketone

Specific example:



$$CH_3-\overset{\displaystyle OH}{\underset{\displaystyle H}{C}}-CH_3+(O)\longrightarrow CH_3-\overset{\displaystyle O}{\overset{\|}{C}}-CH_3+H_2O \qquad (13.11)$$

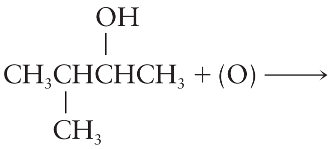
2-propanol

acetone

Secondary alcohols are oxidized to ketones in exactly the same way primary alcohols are oxidized to aldehydes, and by the same oxidizing agents. However, unlike aldehydes, ketones resist further oxidation, so this reaction provides an excellent way to prepare ketones.

Example 13.8 More Oxidation Reactions

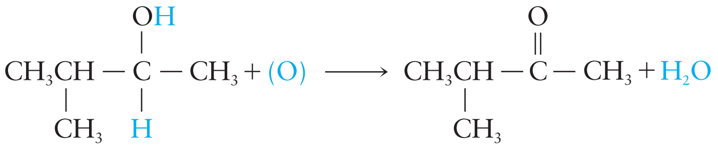
Complete the following oxidation reaction:



$$CH_3\underset{\displaystyle CH_3}{CH}\overset{\displaystyle OH}{CH}CH_3+(O)\longrightarrow$$

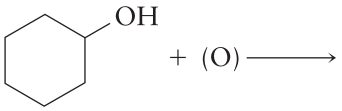
Solution

This reaction is similar to Key Reaction 13.10, where a secondary alcohol is oxidized to a ketone.



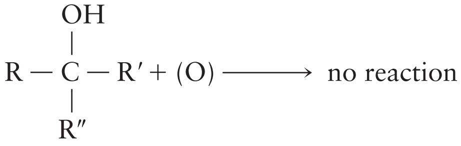
$$\underset{\displaystyle CH_3}{CH_3\underset{|}{CH}}-\overset{\displaystyle OH}{\underset{\displaystyle H}{C}}-CH_3+(O)\longrightarrow \underset{\displaystyle CH_3}{CH_3\underset{|}{CH}}-\overset{\displaystyle O}{\overset{\|}{C}}-CH_3+H_2O$$

✔ **LEARNING CHECK 13.10** Complete the following oxidation reaction:



Tertiary Alcohols. A general reaction is given in Reaction 13.12:

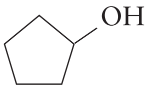
General reaction:

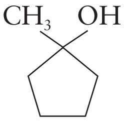


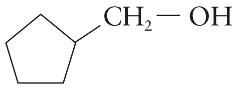
$$R-\overset{\overset{\large OH}{|}}{\underset{\underset{\large R''}{|}}{C}}-R' + (O) \longrightarrow \text{no reaction} \qquad (13.12)$$

Tertiary alcohols do not have any hydrogen on the —OH-bearing carbon and thus do not react with oxidizing agents.

✔ **LEARNING CHECK 13.11** Which of the following alcohols will react with an oxidizing agent?

a. 

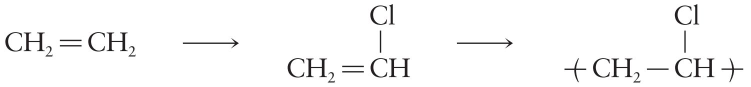
b. 

c. 

13.4D Multistep Reactions

Alcohols are important organic compounds not only for their own commercial applications but because they can be converted by chemical reactions into a wide variety of other useful products. Most alcohols do not occur naturally in commercial quantities and therefore are prepared from alkenes.

It is very common in both laboratory and industrial processes for such preparations to involve a sequence of reactions. For example, the commercial production of vinyl plastic (PVC) begins with the alkene ethene:



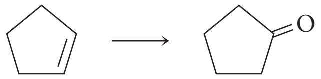
$$CH_2{=}CH_2 \longrightarrow CH_2{=}\overset{\overset{\large Cl}{|}}{CH} \longrightarrow +CH_2-\overset{\overset{\large Cl}{|}}{CH}+$$

ethene — vinyl chloride — poly (vinyl chloride) (PVC)

Nature, too, employs multistep reactions to carry out processes essential to life. The glycolysis pathway used by the body to initiate the utilization of glucose for energy production involves a series of 10 reactions (see **Section 23.3**).

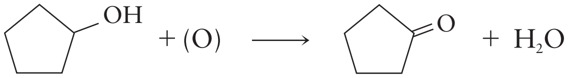
Example 13.9 Writing Multistep Reactions

The following conversion requires more than one step. Show the reaction, reagents, and intermediate structures necessary to carry out the synthesis.

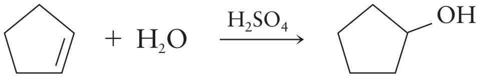


Solution

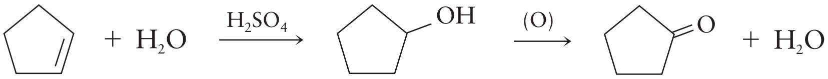
The best way to initially solve a multistep synthesis is to work backward from the final product. Identify the functional group present in the product—in this case, a ketone. Think how to prepare a ketone—by oxidizing an alcohol.



Now, working backward again, think how to prepare an alcohol—from an alkene through hydration.



Adding these two steps together gives



LEARNING CHECK 13.12 Show the reactions necessary to carry out the following conversion.

$$CH_2{=}CH_2 \longrightarrow CH_3CH_2{-}O{-}CH_2CH_3$$

13.5 Important Alcohols

Learning Objective 5 Recognize uses for specific alcohols.

The simplest alcohol, methanol or methyl alcohol, is a very important industrial chemical; more than 1 billion gallons are produced and used annually. It is sometimes known as wood alcohol because the principal source for many years was the distillation of wood. Today, it is synthetically produced in large quantities by reacting hydrogen gas with carbon monoxide (Reaction 13.13):

$$CO + 2H_2 \xrightarrow[\text{heat, pressure}]{\text{Catalysts}} CH_3{-}OH \qquad (13.13)$$

The industrial importance of methanol is due to its oxidation product, formaldehyde, which is a major starting material for the production of plastics. Methanol is used as a fuel in Indy-style racing cars (see **Figure 13.12**). It is also used as a fuel in products such as alcohol burners found in camping supplies.

Jello5700/iStock/Getty Images

FIGURE 13.12 Racing cars are fueled by methanol. What would be the equation for the combustion of methanol?

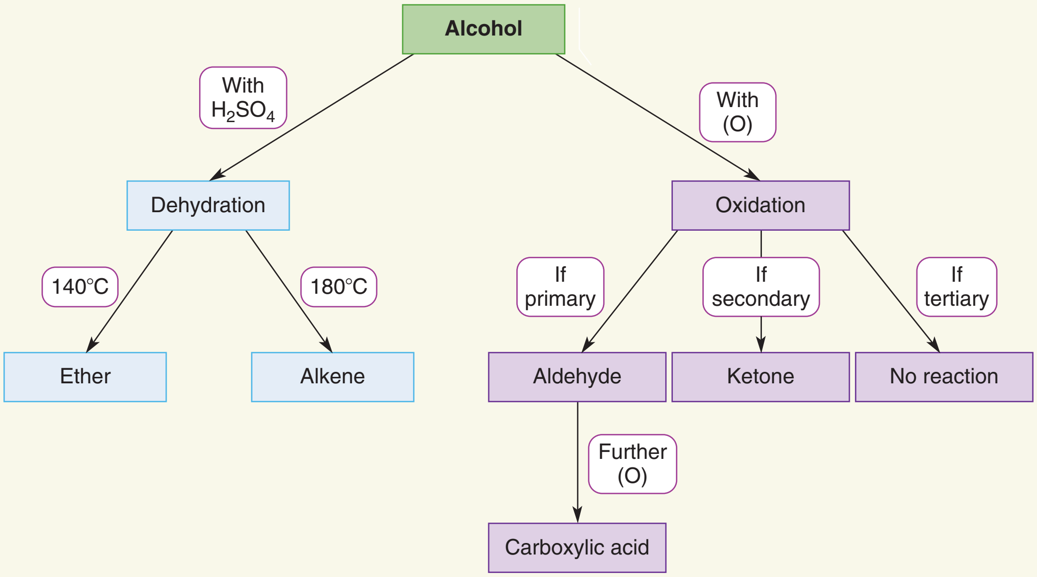
Methanol is highly toxic and causes permanent blindness if taken internally. Deaths and injuries have resulted as a consequence of mistakenly substituting methanol for ethyl alcohol in beverages.

Ethanol, or ethyl alcohol, $CH_3CH_2{-}OH$, is probably the most familiar alcohol because it is the active ingredient in alcoholic beverages. It is also used in pharmaceuticals as a solvent (tinctures are ethanol solutions) and in aftershave lotions as an antiseptic and skin

STUDY TOOLS 13.1

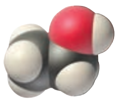
A Reaction Map for Alcohols

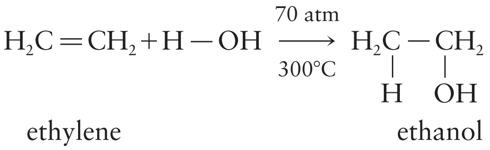
To solve a test question, using a stepwise approach is often helpful. First, decide what type of question is being asked. Is it a nomenclature, typical uses, physical properties, or a reaction question? Second, if you recognize it as, say, a reaction question, look for the functional group. Third, if there is an alcohol group in the starting material, identify the reagent and use the following diagram to predict the right products.



softener. It is an important industrial solvent as well. The gasohol now marketed at many locations around the United States is a mixture of ethanol and gasoline.

Most ethanol used industrially is produced on a large scale by the direct hydration of ethylene obtained from petroleum (Reaction 13.14):


Ethanol



$$\underset{\text{ethylene}}{H_2C{=}CH_2} + H{-}OH \xrightarrow[300^\circ C]{70\text{ atm}} \underset{\text{ethanol}}{\underset{H\quad\;\; OH}{H_2C{-}CH_2}} \qquad (13.14)$$

Ethanol for beverages and increasingly for gasohol is produced by the yeast **fermentation** of carbohydrates such as sugars, starch, and cellulose. For example, a common method is the fermentation of glucose, grape sugar (Reaction 13.15):

fermentation A reaction of sugars, starch, or cellulose to produce ethanol and carbon dioxide.

$$\underset{\text{glucose}}{C_6H_{12}O_6} \xrightarrow{\text{Yeast}} \underset{\text{ethanol}}{2CH_3CH_2-OH} + 2CO_2 \qquad (13.15)$$

2-propanol (isopropyl alcohol), the main component of rubbing alcohol, acts as an astringent on the skin. It causes tissues to contract, hardens the skin, and limits secretions. Its rapid evaporation from the skin also lowers the skin temperature. It is used as an antiseptic in 70% solutions (see **Figure 13.13**). Isopropyl alcohol is toxic and should not be taken internally.

thodonal88/Shutterstock.com

FIGURE 13.13 Isopropyl alcohol is used as an antiseptic before an injection.

HEALTH CONNECTIONS 13.1

Alcohol and Antidepressants Don't Mix

Individuals suffering from depression often demonstrate one or more of the following symptoms: extreme feelings of sadness or melancholy, feelings of inadequacy in facing life's challenges, inability to make decisions, physical inactivity, lack of appetite, inability to sleep, and frequent crying.

Antidepressant medications are designed to counteract these symptoms. However, when alcohol, itself a depressant, is combined with antidepressant medications, serious consequences can result. For example, some antidepressants cause sedation and drowsiness. Alcohol has similar effects, and the combination of the two could easily cause a person to fall asleep while driving. Initially, alcohol might seem to improve the mood of a depressed person, but its overall effect is often to increase the symptoms of depression.

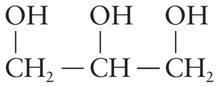
The combination of some types of antidepressants and alcohol influences coordination, judgment, and reaction time and other motor skills more than alcohol alone. When combined with certain types of alcoholic beverages and foods, antidepressants known as monoamine oxidase inhibitors (MAOIs) cause bodily reactions such as a dangerous increase in blood pressure.

It has been found that people suffering from depression have an increased risk of becoming addicted to alcohol or other addictive substances. Clearly, when these factors are all taken into consideration, it is not worth the risks for people being treated for depression to mix their antidepressant medications with alcohol.

Alyssa White

When alcohol is combined with antidepressants, serious consequences can result.

1,2,3-propanetriol is known more commonly as glycerol or glycerin:

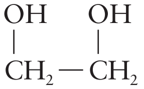


$$\begin{array}{ccccc} OH & & OH & & OH \\ | & & | & & | \\ CH_2 & - & CH & - & CH_2 \end{array}$$

1,2,3-propanetriol (glycerol)

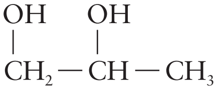
The hydrogen bonding resulting from the three hydroxy groups causes glycerol to be a syrupy, high-boiling-point liquid with an affinity for water. This property and its nontoxic nature make it valuable as a moistening agent in tobacco and many food products, such as candy and shredded coconut. Florists use glycerol to retain water, which maintains the freshness of cut flowers. Glycerol is also used for its soothing qualities in shaving and toilet soaps and in many cosmetics. In **Chapter 18** on lipids, we will see that glycerol forms part of the structure of body fats and oils.

Due to hydrogen bonding, 1,2-ethanediol (ethylene glycol) and 1,2-propanediol (propylene glycol) are both high-boiling liquids that are completely miscible with water.



$$\begin{array}{ccc} OH & & OH \\ | & & | \\ CH_2 & - & CH_2 \end{array}$$

1,2-ethanediol
(ethylene glycol)



$$\begin{array}{ccccc} OH & & OH & & \\ | & & | & & \\ CH_2 & - & CH & - & CH_3 \end{array}$$

1,2-propanediol
(propylene glycol)

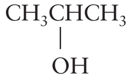
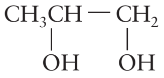
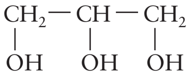
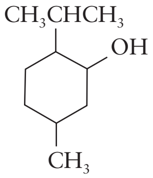
Their main uses are as automobile antifreeze (see **Figure 13.14**) and as a starting material for the manufacture of polyester fibers (Reaction 15.11).

Alcohols are very important biologically because the alcohol functional group occurs in a variety of compounds associated with biological systems (see **Figure 13.15**). For example, sugars contain several hydroxy groups, and starch and cellulose contain thousands of hydroxy groups (see **Chapter 17**). The structures and uses of some common alcohols are summarized in **Table 13.2**.

Maren Hansen

FIGURE 13.14 Ethylene glycol ($HO—CH_2CH_2—OH$) is used as an automotive antifreeze.

TABLE 13.2 Examples of Alcohols

Name	Structural Formula	Typical Uses
Methanol (methyl alcohol)	$\mathrm{CH_3{-}OH}$	Solvent, making formaldehyde
Ethanol (ethyl alcohol)	$\mathrm{CH_3CH_2{-}OH}$	Solvent, alcoholic beverages
2-propanol (isopropyl alcohol)	 $\mathrm{CH_3}\underset{\mathrm{OH}}{\underset{\vert}{\mathrm{CH}}}\mathrm{CH_3}$	Rubbing alcohol, solvent
1-butanol (butanol)	$\mathrm{CH_3CH_2CH_2CH_2{-}OH}$	Solvent, hydraulic fluid
1,2-ethanediol (ethylene glycol)	$\mathrm{HO{-}CH_2CH_2{-}OH}$	Automobile antifreeze, polyester fibers
1,2-propanediol (propylene glycol)	 $\mathrm{CH_3}\underset{\mathrm{OH}}{\underset{\vert}{\mathrm{CH}}}-\underset{\mathrm{OH}}{\underset{\vert}{\mathrm{CH_2}}}$	Moisturizer in lotions and foods, automobile antifreeze
1,2,3-propanetriol (glycerin, glycerol)	 $\underset{\mathrm{OH}}{\underset{\vert}{\mathrm{CH_2}}}-\underset{\mathrm{OH}}{\underset{\vert}{\mathrm{CH}}}-\underset{\mathrm{OH}}{\underset{\vert}{\mathrm{CH_2}}}$	Moisturizer in foods, tobacco, and cosmetics
Menthol		Cough drops, shaving lotion, mentholated tobacco

✔ **LEARNING CHECK 13.13** What is an important use for each of the following alcohols?

a. methanol
b. ethanol
c. 2-propanol
d. ethylene glycol
e. glycerol
f. menthol

ASSURED
MENTHOL EUCALYPTUS
COUGH DROPS
35 drops

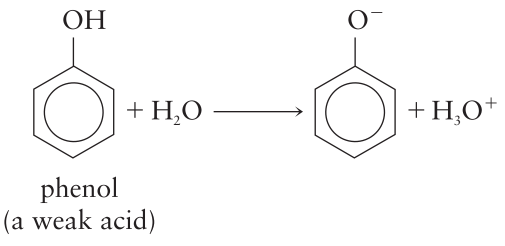
jfmdesign/iStock Unreleased/Getty Images

FIGURE 13.15 Numerous products contain naturally occurring menthol (cough drops, throat sprays, aftershave lotions, chest rubs, and toothpaste) because of its refreshing, cooling sensation on the skin.

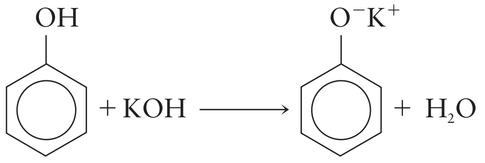
13.6 Characteristics and Uses of Phenols

Learning Objective 6 Recognize uses for specific phenols.

Phenol, C_6H_5OH, is a colorless, low-melting-point solid with a medicinal odor. The addition of a small amount of water causes the solid to liquefy at room temperature. This liquid mixture is sometimes called carbolic acid. Unlike alcohols, phenols are weak acids (Reactions 13.16 and 13.17), which can damage skin by denaturing the proteins in the skin (see **Figure 13.16**), and they must be handled with care.



(13.16)

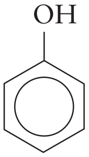


(13.17)

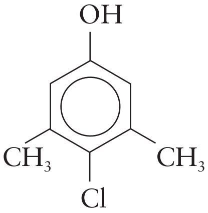
Kyle Selcer/Shutterstock.com

FIGURE 13.16 Rashes associated with poison ivy are caused by phenolic compounds present in the leaves.

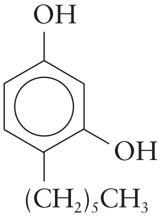
In dilute solutions, phenol is used as an antiseptic and disinfectant. Joseph Lister, an English surgeon, introduced the use of phenol as a hospital antiseptic in the late 1800s. Before that time, antiseptics had not been used, and very few patients survived even minor surgery because of postoperative infections. Today, there are effective derivatives used as antiseptics instead of phenol that are less irritating to the skin. Two such compounds, 4-chloro-3,5-dimethylphenol and 4-hexylresorcinol, are shown here.



phenol
(Lister's original
disinfectant)

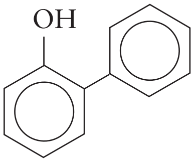


4-chloro-3,5-dimethylphenol
(nonirritating topical
antiseptic)

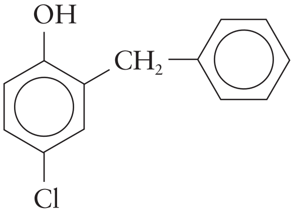


4-hexylresorcinol
(used in mouthwashes
and throat lozenges)

Two other derivatives of phenol, *o*-phenylphenol and 2-benzyl-4-chlorophenol, are ingredients in Lysol®, a disinfectant for walls and furniture in hospitals and homes:



o-phenylphenol

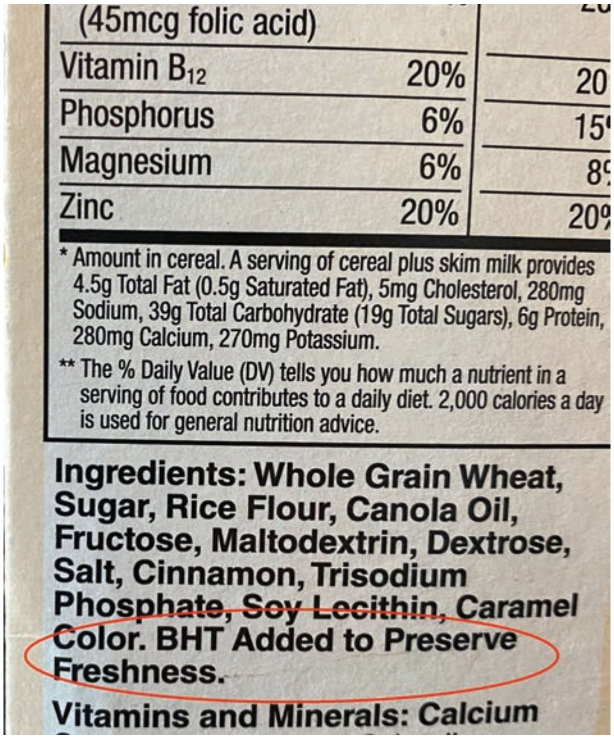


2-benzyl-4-chlorophenol

antioxidant A substance that prevents another substance from being oxidized.

Other important phenols act as **antioxidants** by interfering with oxidizing reactions. These phenols are useful in protecting foods from spoilage and a variety of other materials from unwanted reactions. Butylated hydroxy anisole (BHA) and butylated hydroxy toluene (BHT) are widely used as antioxidants in gasoline, lubricating oils, rubber, certain foods, and packaging materials for foods that might turn rancid (see **Figure 13.17**). In food or

FIGURE 13.17 BHT is listed as a food or packaging ingredient that will "maintain freshness."



(45mcg folic acid)		
Vitamin B$_{12}$	20%	20
Phosphorus	6%	15
Magnesium	6%	8
Zinc	20%	20

* Amount in cereal. A serving of cereal plus skim milk provides 4.5g Total Fat (0.5g Saturated Fat), 5mg Cholesterol, 280mg Sodium, 39g Total Carbohydrate (19g Total Sugars), 6g Protein, 280mg Calcium, 270mg Potassium.

** The % Daily Value (DV) tells you how much a nutrient in a serving of food contributes to a daily diet. 2,000 calories a day is used for general nutrition advice.

Ingredients: Whole Grain Wheat, Sugar, Rice Flour, Canola Oil, Fructose, Maltodextrin, Dextrose, Salt, Cinnamon, Trisodium Phosphate, Soy Lecithin, Caramel Color. BHT Added to Preserve Freshness.

Vitamins and Minerals: Calcium

HEALTH CONNECTIONS 13.2

Take Advantage of Hand Sanitizers

Hospitals, schools, and businesses often provide alcohol-based hand sanitizers to the public. Wall-mounted dispensers of foams and gels or wipes designed to sanitize a shopping cart offer safety, but do you feel comfortable using them? Do they really make a difference for the better?

According to the Centers for Disease Control and Prevention (CDC), proper hand sanitizer use does offer significant safe and healthy benefits. Clean hands prevent the spread of disease and help keep the public healthy. When available, plain soap and water is the best choice for cleaning hands. Rubbing the hands together with soap mechanically removes grime and germs, and the water rinses them away. Washing for at least 20 seconds with soap and water has been shown to remove microbes, and is the preferred method to use for hand cleaning. However, soap and water might not always be available. That is when hand sanitizers can provide a useful alternative.

The CDC recommends that only alcohol-based hand sanitizers with an alcohol content between 60 and 95% be used. Non–alcohol-based hand sanitizers might actually contribute to the spread of resistant bacteria because they only reduce the growth rate of germs rather than kill them outright.

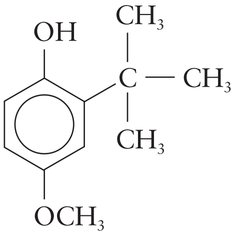
Alcohol-based hand sanitizers kill germs effectively and help prevent the spread of disease, but there are some safety concerns. Adults should supervise children when they are using hand sanitizers to ensure that they do not ingest the product. Adults should make sure that the sanitizer is completely dry on their hands before children are allowed to eat or drink anything.

Also, since alcohol is flammable, hand sanitizers should be stored away from sources of heat. Some non–alcohol-based sanitizers contain triclosan. This is an antibacterial product that has been shown to interfere with hormone regulation in animals, promote the growth of antibiotic-resistant bacteria, and might be harmful to immune systems. Despite these few safety risks, research regarding alcohol-based hand sanitizers suggests that conscientious and proper use of these products is a positive step in preventing the spread of disease and protecting individual health by reducing infection.

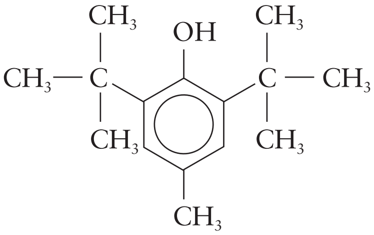
Zyn Chakrapong/Shutterstock.com

The use of hand sanitizers helps prevent the spread of disease.

containers used to package food, the amount of these antioxidants is limited to 200 ppm (parts per million) or 0.02%, based on the fat or oil content of the food. Notice that industrial nomenclature for these compounds does not follow IUPAC rules.



BHA (butylated hydroxy anisole)
2-*t*-butyl-4-methoxyphenol
(IUPAC name)



BHT (butylated hydroxy toluene)
2, 6-di-*t*-butyl-4-methylphenol
(IUPAC name)

✔ **LEARNING CHECK 13.14** What is an important use for each of the following phenols?

a. BHA b. 4-hexylresorcinol

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

13.7 Ethers

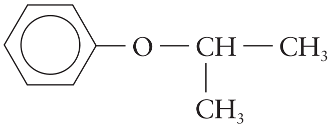
Learning Objective 7 Name and draw structural formulas for ethers.

Dimethyl ether

Ethers were introduced at the start of this chapter as compounds whose formula is R—O—R′. Common names for ethers are obtained by first naming the two groups attached to the oxygen and then adding the word *ether.* If the groups are the same, it is appropriate to use the prefix *di-,* as in diethyl ether, but many people omit the *di-* and simply say "ethyl ether."

$CH_3-O-CH_2CH_3$

ethyl methyl ether



isopropyl phenyl ether

CH_3-O-CH_3

dimethyl ether
(methyl ether)

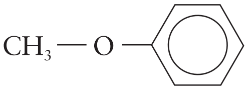
$CH_3CH_2-O-CH_2CH_3$

diethyl ether
(ethyl ether)

Example 13.10 Naming Ethers

Assign a common name to the following ethers:

a.



b. $CH_3CH_2CH_2-O-CH_2CH_2CH_3$

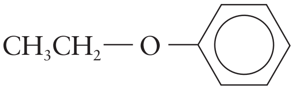
Solution

a. Common names for ethers are formed by naming the two groups attached to the oxygen and adding the word *ether*.
The common name is methyl phenyl ether

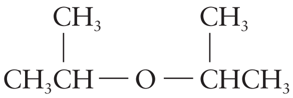
b. If the two groups attached to the oxygen are the same, the prefix *di-* is used. The common name is dipropyl ether

✔ LEARNING CHECK 13.15 Assign a common name to the following:

a.



b.



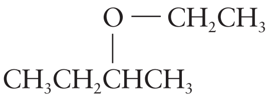
$$CH_3\overset{\overset{\displaystyle CH_3}{|}}{CH}-O-\overset{\overset{\displaystyle CH_3}{|}}{CH}CH_3$$

alkoxy group The —O—R functional group.

In the IUPAC naming system for ethers, the —O—R group is called an **alkoxy group**. The *-yl* ending of the smaller R group is replaced by *-oxy.* For example, $—O—CH_3$ is called a methoxy group, $—O—CH_2CH_3$ is called ethoxy, and so on:

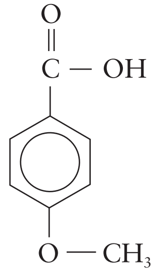
CH_3-O-CH_3

methoxymethane



$$CH_3CH_2\overset{\overset{\displaystyle O-CH_2CH_3}{|}}{C}HCH_3$$

2-ethoxybutane

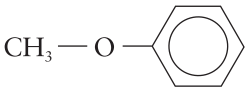


p-methoxybenzoic acid

Example 13.11 More Naming Ethers

Give an IUPAC name to the following ethers:

a.

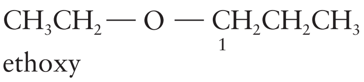


b. $CH_3CH_2—O—CH_2CH_2CH_3$

Solution

a. The benzene ring has more carbon atoms, so it is chosen as the base word. The CH_3—O— group is called methoxy, and the complete name is methoxybenzene.

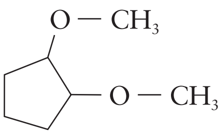
b. The longest carbon chain contains three carbon atoms. The base word is propane. At position 1 is an ethoxy group; the complete name is 1-ethoxypropane.



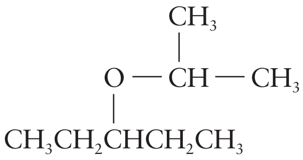
$$\underbrace{CH_3CH_2}_{\text{ethoxy}}—O—\underset{1}{C}H_2CH_2CH_3$$

✔ LEARNING CHECK 13.16 Give IUPAC names for the following:

a.

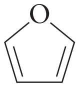


b.

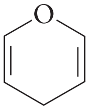


The ether linkage is also found in cyclic structures. A ring that contains elements in addition to carbon is called a **heterocyclic ring**. Two common structures with oxygen-containing heterocyclic rings are:

heterocyclic ring A ring containing at least one atom of an element other than carbon.



furan



pyran

Many carbohydrates contain the fundamental ring systems of furan and pyran (see **Chapter 17**).

13.8 Properties of Ethers

Learning Objective 8 Describe the key physical and chemical properties of ethers.

The oxygen atom of ethers can form hydrogen bonds with water (see **Figure 13.18a**), so ethers are slightly more soluble in water than hydrocarbons but less soluble than alcohols of comparable molecular weight. Ethers, however, cannot form hydrogen bonds with other ether molecules in the pure state (see **Figure 13.18b**), which results in low boiling points close to those of hydrocarbons with similar molecular weights.

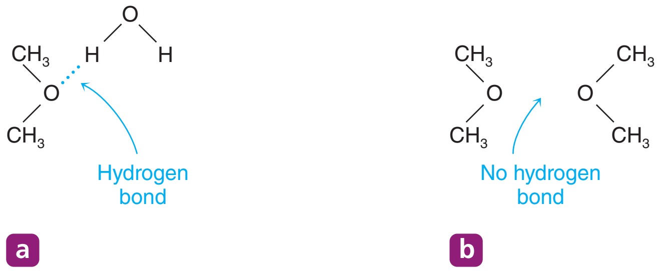


FIGURE 13.18 Hydrogen bonding of dimethyl ether: (a) with water and (b) no hydrogen bonding in the pure state.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS 13.3

General Anesthetics

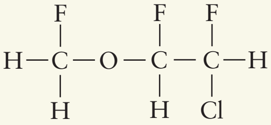
Anesthetics are compounds that induce a loss of sensation in a specific part (local anesthetic) or all (general anesthetic) of the body. A general anesthetic acts on the brain to produce unconsciousness as well as insensitivity to pain.

The word *ether* is often associated with general anesthetics because of the well-known use of ethyl ether for this purpose. Ethyl ether became generally used as an anesthetic for surgical operations in about 1850. Before that time, surgery was an agonizing procedure. The patient was strapped to a table and (if lucky) soon fainted from the pain. Divinyl ether (Vinethene) is an anesthetic that acts more rapidly and is less nauseating than ethyl ether:

$$CH_2{=}CH{-}O{-}CH{=}CH_2$$

divinyl ether

Another common ether anesthetic is enflurane:



$$\begin{array}{ccccccccccc} & & F & & & & F & & F & & \\ & & | & & & & | & & | & & \\ H & - & C & - & O & - & C & - & C & - & H \\ & & | & & & & | & & | & & \\ & & H & & & & H & & Cl & & \end{array}$$

enflurane

Numerous inhalation anesthetics are not ethers at all. Nitrous oxide, for example, is a simple inorganic compound with the formula N_2O. Also known as "laughing gas," it is used as a general anesthetic by some dentists because its effects wear off quickly.

Marius Pirvu/Shutterstock.com

A patient receives an anesthetic prior to dental surgery.

The chief chemical property of ethers is that, like the alkanes, they are inert and do not react with most reagents. It is this property that makes diethyl ether such a useful solvent. Like hydrocarbons, ethers are flammable, and diethyl ether is especially flammable because of its high volatility. Diethyl ether was the first general anesthetic used in surgery. For many years, it was the most important compound used as an anesthetic, but it has now been largely replaced by other compounds.

✔ **LEARNING CHECK 13.17**

a. Explain why an ether boils at a lower temperature than an alcohol of similar molecular weight.

b. What is the most significant chemical property of ethers?

13.9 Thiols

Learning Objective 9 Write equations for a thiol reaction with heavy metal ions and the production of disulfides that results when thiols are oxidized.

Sulfur and oxygen belong to the same group of the periodic table, so it is not surprising that they form similar compounds. The sulfur counterparts (analogues) of alcohols contain an —SH group rather than an —OH group and are called **thiols** (an older name is mercaptans). The —SH is known as a **sulfhydryl group**.

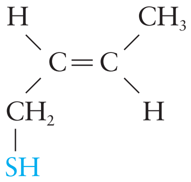
thiol A compound containing an —SH group.

sulfhydryl group The —SH functional group.

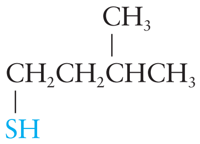
$$R{-}OH \qquad\qquad R{-}SH$$

alcohol   thiol

Perhaps the most distinguishing feature of thiols is their strong and disagreeable odors. Two different thiols and a disulfide are responsible for the odor associated with skunks (see **Figure 13.19**).

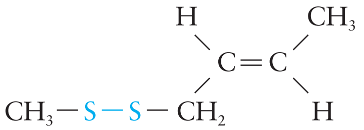


trans-2-butene-1-thiol



$$\underset{SH}{CH_2}CH_2\overset{CH_3}{CH}CH_3$$

3-methyl-1-butanethiol



methyl-1-(*trans*-2-butenyl)disulfide

James Coleman/Shutterstock.com

FIGURE 13.19 Skunks use thiol chemistry as an effective defense mechanism. Thiols are more volatile than alcohols but less soluble in water. Why are these characteristics an advantage to skunks?

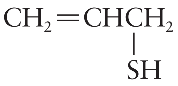
Some less-offensive odors (and flavors) are also characteristic of thiols and disulfides. Freshly chopped onions emit propanethiol, and 1-propene-3-thiol and 3,3-di-(1-propenyl) disulfide are partially responsible for the odor and flavor of garlic (see **Figure 13.20**). It is amazing that the simple substitution of a sulfur atom for an oxygen atom can cause such a dramatic change in odor.

monicore/1127 images/Pixabay

FIGURE 13.20 The reputation of garlic and onions for producing bad breath is due to the presence of sulfur compounds.

$CH_3CH_2CH_2-SH$

propanethiol



$$CH_2{=}CH\underset{SH}{CH_2}$$

1-propene-3-thiol

$CH_2{=}CHCH_2-S-S-CH_2CH{=}CH_2$

3,3-di-(1-propenyl)disulfide

Gas companies make effective use of the odor of thiols. Natural gas (methane) has no odor, so the companies add a tiny amount of a thiol such as ethanethiol (CH_3CH_2—SH) to make it possible to detect leaking gas before a spark or match sets off an explosion.

Two reactions of the —SH group are important in the chemistry of proteins. When thiols are oxidized by agents such as O_2, a coupling reaction occurs (two molecules become one) to form a **disulfide**, a compound containing an —S—S— linkage:

disulfide A compound containing an —S—S— group.

General reaction:

$$\underset{\text{a thiol}}{2R-SH}+(O) \rightarrow \underset{\text{a disulfide}}{R-S-S-R}+H_2O \qquad (13.18)$$

Specific example:

$$2CH_3-SH+(O) \rightarrow CH_3-S-S-CH_3+H_2O \qquad (13.19)$$

Example 13.12 Oxidation of Thiols

Propanethiol, a foul-smelling component of onions, can undergo oxidation. Complete the following reaction:

$$2CH_3CH_2CH_2—SH + (O) \rightarrow$$

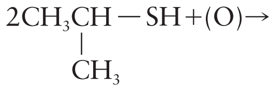
Solution

This reaction is similar to Key Reaction 13.18, in which a water molecule forms as two thiols come together forming a disulfide linkage.

cough drops, throat sprays, aftershave lotions, chest rubs, and toothpaste

$$2CH_3CH_2CH_2—SH + (O) \rightarrow CH_3CH_2CH_2—S—S—CH_2CH_2CH_3 + H_2O$$

✔ LEARNING CHECK 13.18 Complete the following reaction:



$$2CH_3\underset{\displaystyle CH_3}{\underset{|}{CH}}-SH+(O)\rightarrow$$

Disulfide linkages are important structural features of some proteins, especially those of hair (see **Section 19.6**). The coupling reaction can be reversed by treating disulfides with a reducing agent (H) such as H_2, which regenerates the thiol:

General reaction:

$$R—S—S—R + 2(H) \rightarrow 2R—SH \qquad (13.20)$$

Specific example:

$$CH_3—S—S—CH_3 + 2(H) \rightarrow 2CH_3—SH \qquad (13.21)$$

Example 13.13 Reduction of Disulfides

Methyl propyl disulfide is partially responsible for the odor of garlic. Complete the following reaction of methyl propyl disulfide:

$$CH_3—S—S—CH_2CH_2CH_3 + 2(H) \rightarrow$$

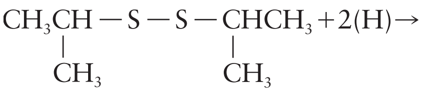
Solution

Using Key Reaction 13.20 as a guide, the disulfide linkage should split, giving two thiol structures.

$$CH_3—S—H \text{ and } H—S—CH_2CH_2CH_3$$

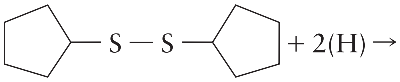
✔ LEARNING CHECK 13.19 What products result from the reduction of the following disulfides?

a.



$$CH_3\underset{\displaystyle CH_3}{\underset{|}{CH}}-S-S-\underset{\displaystyle CH_3}{\underset{|}{CH}}CH_3+2(H)\rightarrow$$

b.



The reaction of thiols with heavy metal ions, such as those of lead and mercury, to form insoluble compounds has adverse biological results. The metal ions (M^{2+}) react with sulfhydryl groups in the following way:

General reaction:

$$2R{-}S{\color{cyan}H} + M^{2+} \rightarrow R{-}S{-}M{-}S{-}R + 2{\color{cyan}H^+} \qquad (13.22)$$

Specific example:

$$2CH_3{-}S{\color{cyan}H} + Hg^{2+} \rightarrow CH_3{-}S{-}Hg{-}S{-}CH_3 + 2{\color{cyan}H^+} \qquad (13.23)$$

Many enzymes (catalysts for biological reactions— see **Section 20.7**) contain —SH groups. Exposure to heavy metal ions ties up these groups, through Reaction 13.22, rendering the enzyme ineffective. The loss of enzymes in this manner can lead to serious biological consequences.

Example 13.14 More Reactions of Thiols

Part of the toxicity of lead and mercury is due to their reaction with essential thiol compounds in the body. Complete the following reaction:

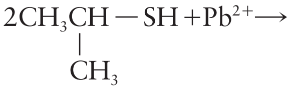
$$2\ CH_3CH_2CH_2{-}SH + Pb^{2+} \rightarrow$$

Solution

Using Key Reaction 13.22 as a guide, the Pb should bond to two sulfur atoms, producing

$$CH_3CH_2CH_2{-}S{-}Pb{-}S{-}CH_2CH_2CH_3 + 2H^+$$

✔ **LEARNING CHECK 13.20** Complete the following reaction:



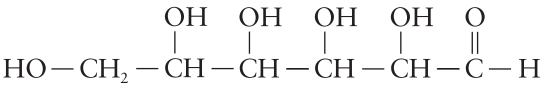
$$2CH_3\underset{\substack{|\\ CH_3}}{CH}{-}SH + Pb^{2+} \longrightarrow$$

13.10 Polyfunctional Compounds

Learning Objective 10 Identify functional groups in polyfunctional compounds.

So far our study of organic molecules has included several compounds with more than one functional group. Compounds of this type, such as dienes and diols, are said to be **polyfunctional compounds**. Substances with different functional groups are also referred to as polyfunctional. Compounds with multiple functional groups are very common in nature, and many play essential roles in life processes. Carbohydrate structures (see **Chapter 17**) such as glucose, typically involve a functional group at every carbon position.

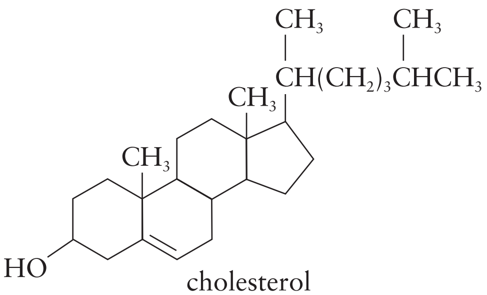
polyfunctional compound A compound with two or more functional groups.



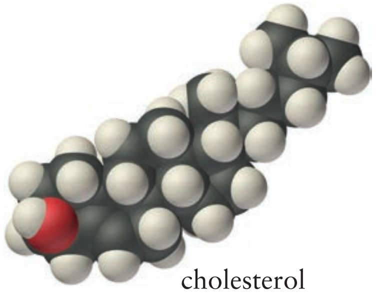
$$HO{-}CH_2{-}\overset{\substack{OH\\ |}}{CH}{-}\overset{\substack{OH\\ |}}{CH}{-}\overset{\substack{OH\\ |}}{CH}{-}\overset{\substack{OH\\ |}}{CH}{-}\overset{\substack{O\\ \|}}{C}{-}H$$

glucose

Even though some organic structures look quite complex, with multiple rings and long carbon chains, remember that it's the functional group or groups that determine the chemical properties of the compound. Thus, cholesterol, with two functional groups, should exhibit the reactions of both alkenes and alcohols.



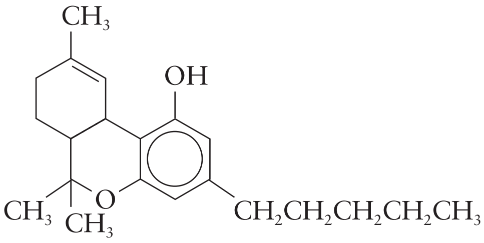
cholesterol



cholesterol

Example 13.15 Identifying Functional Groups

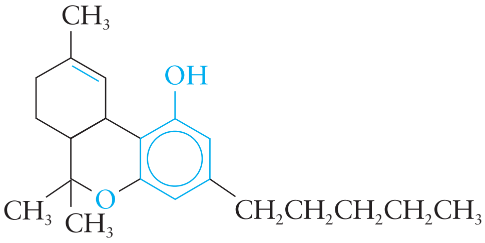
Identify the functional groups in tetrahydrocannabinol, the active ingredient in marijuana.



tetrahydrocannabinol

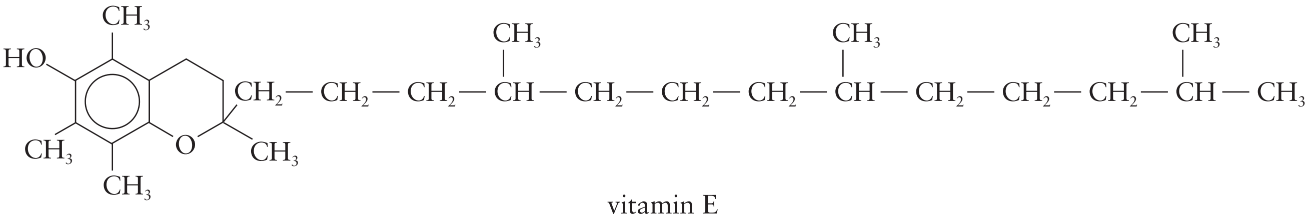
Solution

To find functional groups, look for unique atoms or collections of atoms while ignoring ordinary rings, chains, and alkyl groups. Look for multiple bonds and atoms other than carbon. The tetrahydrocannabinol molecule has four functional groups: an ether, a phenolic —OH, the benzene ring, and a carbon–carbon double bond.



tetrahydrocannabinol

✔ LEARNING CHECK 13.21 Identify the functional groups in vitamin E.



vitamin E

Health Career Description

REHABILITATION COUNSELOR/TECHNICIAN

Rehabilitation counselors or technicians provide support to patients in either inpatient or outpatient treatment programs. They may participate in counseling sessions or group therapy, administration of medications, and adherence to behavioral (consequence and reward) treatment programs. They provide empathetic support and encouragement as well as help maintain adherence to behavioral standards. They may be required to take a client's vital signs and to administer, observe, and/or document urinalysis tests or breath alcohol tests.

Strong communication skills, or "soft skills" are extremely important in this line of work, as is meticulous attention to detail and an ability to keep accurate records and maintain patient confidentiality and privacy rules.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

A job announcement for a Denver Colorado treatment center listed the following duties for rehabilitation technicians:

- Adheres to Community Reach Center Code of Ethics as well as ethical standards of the field.
- Assists with the planning, conducting, and supervision of activities of the client population.
- Attends and participates in staff meetings, training classes, and supervision.
- Documents all significant interactions with each client.
- Interacts with consumer population in order to provide guidance, safety, stability, and direction.
- May provide transportation for consumers in center vehicles when clinically indicated and in accordance with hospital contracts.
- Medication monitoring and administration in accordance with Qualified Medication Administration Person (QMAP) standards.
- Monitors and documents client vital signs, physical condition and behavior as needed.
- Monitors milieu activities and ensures safety.
- Monitors the facility to insure it is maintained in a neat and orderly manner and that all outside doors remain secured.
- Conducts intake and discharges.
- Monitors/observes Urinalysis (UA) or Breath Alcohol (BA) tests as needed and documents appropriately.
- Provides case management services assisting clients with information access, resource direction, and support counseling.
- Supports client treatment plans and discusses progress toward goals with clients and supports other clinical staff as needed.
- Provides care to consumers in a manner that recognizes the human potential, is empathic and demonstrates unconditional positive regard while promoting safety, comfort, and the therapeutic environment.

Rehabilitation technicians provide vital, compassionate care to vulnerable patients who need targeted expert professional care. They provide an invaluable community service. Technicians may find work at an associate-degree level in health professions or social work, but job opportunities increase at the bachelor-degree level.

Concept Summary

13.1 The Nomenclature of Alcohols and Phenols

Learning Objective: Can you name and draw structural formulas for alcohols and phenols?

- Alcohols are aliphatic compounds that contain the hydroxy functional group (—OH).
- Aromatic compounds with an —OH group attached to the ring are called phenols.
- Several alcohols are well known by common names.
- In the IUPAC system, the characteristic ending *-ol* is used to designate alcohols.
- Phenols are named as derivatives of the parent compound phenol.

13.2 Classification of Alcohols

Learning Objective: Can you classify alcohols as primary, secondary, or tertiary on the basis of their structural formulas?

- Alcohols are classified on the basis of the number of carbon atoms bonded to the carbon that is attached to the —OH group.
- In primary alcohols, the OH-bonded carbon is bonded to one other carbon.
- In secondary alcohols, the OH-bonded carbon is bonded to two other carbons.
- In tertiary alcohols, the OH-bonded carbon is bonded to three other carbons.

13.3 Physical Properties of Alcohols

Learning Objective: Can you discuss how hydrogen bonding influences the physical properties of alcohols?

- Hydrogen bonding can occur between alcohol molecules and between alcohol molecules and water.
- As a result, alcohols have higher boiling points than hydrocarbons of similar molecular weight and low molecular weight alcohols are soluble in water.

13.4 Reactions of Alcohols

Learning Objective: Can you write equations for alcohol dehydration and oxidation reactions?

- Two important reactions of alcohols are dehydration and oxidation.
- Alcohols may be dehydrated in two different ways, depending on the reaction temperature.
- With H_2SO_4 at 180°C, an alkene is produced, whereas at 140°C, the product is an ether.
- The oxidation products obtained from the alcohols depend on the class of alcohol being oxidized.
- A primary alcohol produces an aldehyde that is further oxidized to a carboxylic acid.

- A secondary alcohol produces a ketone.
- A tertiary alcohol does not react with oxidizing agents.

13.5 Important Alcohols

Learning Objective: Can you recognize uses for specific alcohols?

- Some simple alcohols with commercial value are
  - methanol (a solvent and fuel)
  - ethanol (present in alcoholic beverages and gasohol)
  - isopropyl alcohol (rubbing alcohol)
  - ethylene glycol (antifreeze)
  - and glycerol (a moistening agent).

13.6 Characteristics and Uses of Phenols

Learning Objective: Can you recognize uses for specific phenols?

- Phenols are weak acids that are widely used for their antiseptic and disinfectant properties.
- Some phenols are used as antioxidants in foods and a variety of other materials.

13.7 Ethers

Learning Objective: Can you name and draw structural formulas for ethers?

- Ethers contain an oxygen attached to two carbons as the characteristic functional group.
- In the IUPAC system, ethers are named as alkoxy derivatives of alkanes.
- The $-O-R$ group is the alkoxy group that may have names such as methoxy ($-O-CH_3$) or ($-O-CH_2CH_3$).

13.8 Properties of Ethers

Learning Objective: Can you describe the key physical and chemical properties of ethers?

- Like the alkanes, ethers are very unreactive substances.
- Pure ethers cannot form hydrogen bonds.
- As a result, their boiling points are comparable to those hydrocarbons and lower than those of alcohols of similar molecular weight.
- Ethers are much less polar than alcohols but are still slightly soluble in water because of the limited formation of hydrogen bonds.

13.9 Thiols

Learning Objective: Can you write equations for a thiol reaction with heavy metal ions and the production of disulfides that results when thiols are oxidized?

- Thiols contain an $-SH$ group, which often imparts a strong, disagreeable odor to the compound.
- Two reactions of thiols that are important in protein chemistry are their oxidation to produce a disulfide and their reaction with heavy metals such as mercury.
- Disulfides may be converted back to thiols by a reducing agent.

13.10 Polyfunctional Compounds

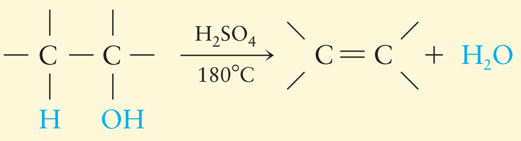
Learning Objective: Can you identify functional groups in polyfunctional compounds?

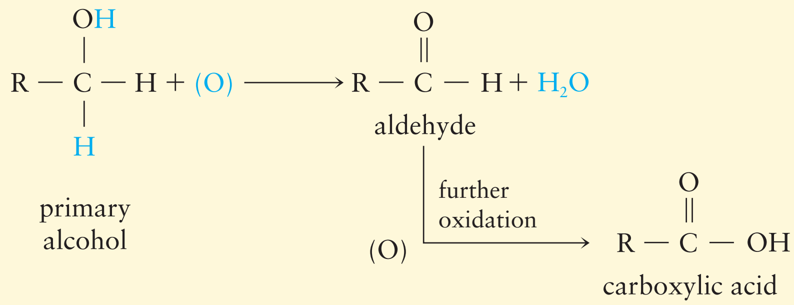
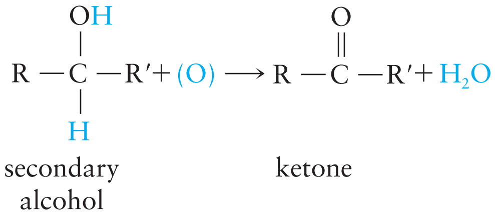
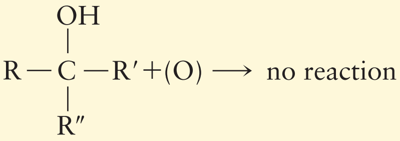
- It is common for organic compounds to contain more than one functional group.
- Many of the compounds that serve essential roles in life processes are polyfunctional.

Key Terms and Concepts

Alcohol (Introduction)
Alkoxy group (13.7)
Antioxidant (13.6)
Dehydration reaction (13.4)
Disulfide (13.9)
Elimination reaction (13.4)
Ether (Introduction)
Fermentation (13.5)
Heterocyclic ring (13.7)
Hydroxy group (Introduction)
Phenol (Introduction)
Polyfunctional compound (13.10)
Primary alcohol (13.2)
Secondary alcohol (13.2)
Sulfhydryl group (13.9)
Tertiary alcohol (13.2)
Thiol (13.9)

Key Reactions

1. Dehydration of alcohols to give alkenes (**Section 13.4**):		Reaction 13.1
2. Dehydration of alcohols to give ethers (**Section 13.4**):	$R-O-H+H-O-R \xrightarrow[140°C]{H_2SO_4} R-O-R+H_2O$	Reaction 13.5

3. Oxidation of a primary alcohol to give an aldehyde and then a carboxylic acid (**Section 13.4**):	 $R-\underset{H}{\overset{OH}{C}}-H + (O) \longrightarrow R-\overset{O}{\overset{\parallel}{C}}-H + H_2O$ primary alcohol aldehyde $\xrightarrow[(O)]{\text{further oxidation}} R-\overset{O}{\overset{\parallel}{C}}-OH$ carboxylic acid	Reaction 13.8
4. Oxidation of a secondary alcohol to give a ketone (**Section 13.4**):	 $R-\underset{H}{\overset{OH}{C}}-R' + (O) \longrightarrow R-\overset{O}{\overset{\parallel}{C}}-R' + H_2O$ secondary alcohol ketone	Reaction 13.10
5. Attempted oxidation of a tertiary alcohol gives no reaction (**Section 13.4**):	 $R-\underset{R''}{\overset{OH}{C}}-R' + (O) \longrightarrow$ no reaction	Reaction 13.12
6. Oxidation of a thiol to give a disulfide (**Section 13.9**):	$2R-SH + (O) \longrightarrow R-S-S-R + H_2O$ a thiol a disulfide	Reaction 13.18
7. Reduction of a disulfide to give thiols (**Section 13.9**):	$R-S-S-R + 2(H) \rightarrow 2R-SH$	Reaction 13.20
8. Reaction of thiols with heavy metals (**Section 13.9**):	$2R-SH + M^{2+} \rightarrow R-S-M-S-R + 2H^{+}$	Reaction 13.22

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

The Nomenclature of Alcohols and Phenols (Section 13.1)

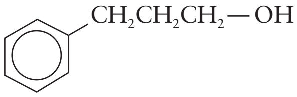
13.1 Draw general formulas for an alcohol and phenol, showing the functional group.

13.2 Draw a general formula for an ether, emphasizing the functional group.

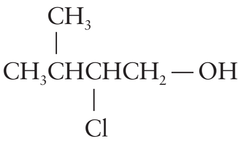
13.3 Assign IUPAC names to the following alcohols:

a. $CH_3CH_2CH_2-OH$

b.

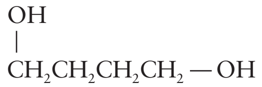


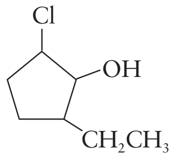
c.

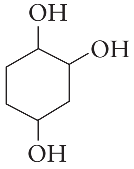


$CH_3\underset{Cl}{CH}\overset{CH_3}{CH}CH_2-OH$

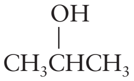
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

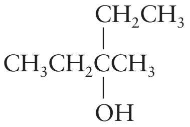
d. 
$\overset{\mathrm{OH}}{\overset{|}{\mathrm{CH_2}}}\mathrm{CH_2CH_2CH_2-OH}$

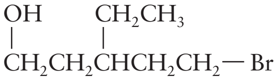
e. 

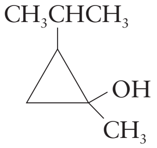
f. 

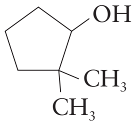
13.4 Assign IUPAC names to the following alcohols:

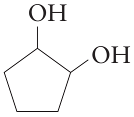
a. 
$\mathrm{CH_3}\overset{\mathrm{OH}}{\overset{|}{\mathrm{C}}}\mathrm{HCH_3}$

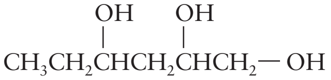
b. 
$\mathrm{CH_3CH_2}\underset{\underset{\mathrm{OH}}{|}}{\overset{\overset{\mathrm{CH_2CH_3}}{|}}{\mathrm{C}}}\mathrm{CH_3}$

c. 
$\overset{\mathrm{OH}}{\overset{|}{\mathrm{CH_2}}}\mathrm{CH_2}\overset{\mathrm{CH_2CH_3}}{\overset{|}{\mathrm{C}}}\mathrm{HCH_2CH_2-Br}$

d. 

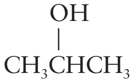
e. 

f. 

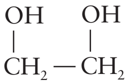
g. 
$\mathrm{CH_3CH_2}\overset{\mathrm{OH}}{\overset{|}{\mathrm{C}}}\mathrm{HCH_2}\overset{\mathrm{OH}}{\overset{|}{\mathrm{C}}}\mathrm{HCH_2-OH}$

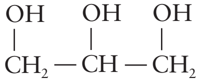
13.5 Several important alcohols are well known by common names. Give a common name for each of the following:

a. CH_3—OH

b. 
$\mathrm{CH_3}\overset{\mathrm{OH}}{\overset{|}{\mathrm{C}}}\mathrm{HCH_3}$

c. CH_3CH_2—OH

d. 
$\overset{\mathrm{OH}}{\overset{|}{\mathrm{CH_2}}}-\overset{\mathrm{OH}}{\overset{|}{\mathrm{CH_2}}}$

e. 
$\overset{\mathrm{OH}}{\overset{|}{\mathrm{CH_2}}}-\overset{\mathrm{OH}}{\overset{|}{\mathrm{CH}}}-\overset{\mathrm{OH}}{\overset{|}{\mathrm{CH_2}}}$

13.6 Give each of the structures in Exercise 13.5 an IUPAC name.

13.7 Draw structural formulas for each of the following:

a. 2-methyl-1-butanol

b. 2-bromo-3-methyl-3-pentanol

c. 1-methylcyclopentanol

13.8 Draw structural formulas for each of the following:

a. 2-methyl-2-pentanol

b. 1,3-butanediol

c. 1-ethylcyclopentanol

13.9 Each of the following alcohols is named incorrectly. Draw structural formulas, and then give the correct IUPAC name for each alcohol.

a. 1,5-cyclohexanediol

b. 3-ethyl-2-butanol

c. 2-ethyl-1-propanol

d. 3,4-pentanediol

13.10 Each of the following alcohols is named incorrectly. Draw structural formulas, and then give the correct IUPAC name for each alcohol.

a. 2,4-butanediol

b. 2-propyl-3-butanol

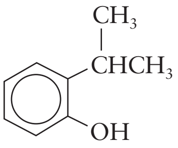
c. 3-methyl-3-butanol

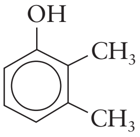
d. 1,4-cyclopentanediol

13.11 Give IUPAC names for all the unbranched (normal) C_7 carbon chain alcohols that only have one —OH group. There are four isomers.

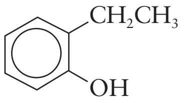
13.12 Give IUPAC names for all the unbranched (normal) C_8 carbon chain alcohols that only have one —OH group. There are four isomers.

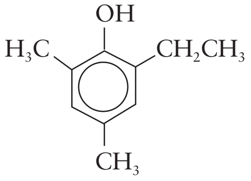
13.13 Name each of the following as a derivative of phenol:

a. 

b. 

13.14 Name each of the following as a derivative of phenol:

a. 

b. 

13.15 Draw structural formulas for each of the following:

a. *m*-methylphenol **b.** 2,3-dichlorophenol

13.16 Draw structural formulas for each of the following:

a. *p*-chlorophenol **b.** 2,5-diisopropylphenol

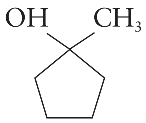
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Classification of Alcohols (Section 13.2)

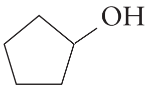
13.17 What is the difference between a primary, secondary, and tertiary alcohol?

13.18 Classify the following alcohols as primary, secondary, or tertiary:

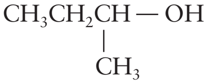
a.



b.



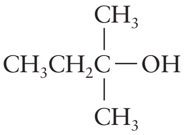
c.



$CH_3CH_2\underset{\underset{\displaystyle CH_3}{|}}{CH}-OH$

13.19 Classify the following alcohols as primary, secondary, or tertiary:

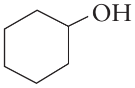
a.



$CH_3CH_2\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-OH$

b. $CH_3CH_2CH_2CH_2-OH$

c.



13.20 Draw structural formulas for the eight aliphatic alcohols with the molecular formula $C_5H_{12}O$. Name each compound using the IUPAC system and classify it as a primary, secondary, or tertiary alcohol.

13.21 Draw structural formulas for the four aliphatic alcohols with the molecular formula $C_4H_{10}O$. Name each compound using the IUPAC system and classify it as a primary, secondary, or tertiary alcohol.

Physical Properties of Alcohols (Section 13.3)

13.22 Why are the boiling points of alcohols much higher than the boiling points of alkanes with similar molecular weights?

13.23 Arrange the compounds of each group in order of increasing boiling point.

a. 1-butanol, 1-pentanol, 1-propanol

b. 1,2-butanediol, 2-butanol, pentane

13.24 Arrange the compounds of each group in order of increasing boiling point.

a. Ethanol, 1-propanol, methanol

b. Butane, Ethylene glycol, 1-propanol

13.25 Which member of each of the following pairs would you expect to be more soluble in water? Briefly explain your choices.

a. 2,3-pentanediol or 2,3,4-pentanetriol

b. Hexane or 3-hexanol

c. 1-butanol or 2-octanol

13.26 Which member of each of the following pairs would you expect to be more soluble in water? Briefly explain your choices.

a. butane or 2-butanol

b. 2-propanol or 2-pentanol

c. 2-butanol or 2,3-butanediol

13.27 Draw structural formulas for the following molecules and use a dotted line to show the formation of hydrogen bonds:

a. one molecule of 3-pentanol and one molecule of 1-propanol

b. 2-propanol and water

13.28 Draw structural formulas for the following molecules and use a dotted line to show the formation of hydrogen bonds:

a. one molecule of 1-butanol and one molecule of ethanol

b. cyclohexanol and water

13.29 Determine the maximum number of hydrogen bonds that can form between a 1-propanol molecule and

a. other 1-propanol molecules

b. water molecules

13.30 Determine the maximum number of hydrogen bonds that can form between a 1-butanol molecule and

a. other 1-butanol molecules

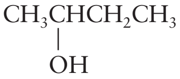
b. water molecules

13.31 Explain why the use of glycerol (1,2,3-propanetriol) in lotions helps retain water and keep the skin moist.

Reactions of Alcohols (Section 13.4)

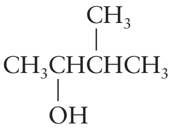
13.32 Draw the structures of the chief product formed when the following alcohols are dehydrated to alkenes:

a.



$CH_3\underset{\underset{\displaystyle OH}{|}}{CH}CH_2CH_3$

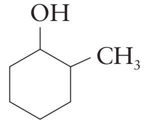
b.



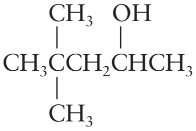
$CH_3\underset{\underset{\displaystyle OH}{|}}{CH}\overset{\overset{\displaystyle CH_3}{|}}{CH}CH_3$

13.33 Draw the structures of the chief product formed when the following alcohols are dehydrated to alkenes:

a.



b.



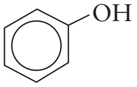
$CH_3\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}CH_2\overset{\overset{\displaystyle OH}{|}}{CH}CH_3$

13.34 Draw the structures of the ethers that can be produced from the following alcohols:

a. CH_3-OH

b. $CH_3CH_2CH_2CH_2-OH$

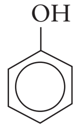
c.



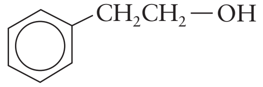
13.35 Draw the structures of the ethers that can be produced from the following alcohols:

a. $CH_3CH_2CH_2-OH$

b.



c.

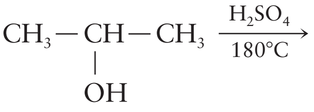


13.36 Draw the structures of the two organic compounds that can be obtained by oxidizing:

$CH_3CH_2CH_2-OH$

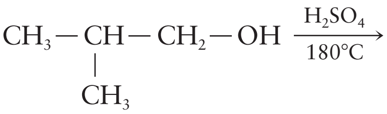
13.37 Draw the structure of the product expected when each of the following alcohols is reacted with a sulfuric acid catalyst at the temperature indicated.

a.



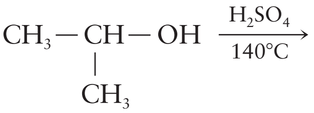
$$CH_3-\underset{OH}{\underset{|}{CH}}-CH_3 \xrightarrow[180^\circ C]{H_2SO_4}$$

b.



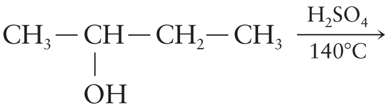
$$CH_3-\underset{CH_3}{\underset{|}{CH}}-CH_2-OH \xrightarrow[180^\circ C]{H_2SO_4}$$

c.



$$CH_3-\underset{CH_3}{\underset{|}{CH}}-OH \xrightarrow[140^\circ C]{H_2SO_4}$$

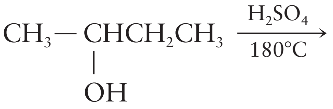
d.



$$CH_3-\underset{OH}{\underset{|}{CH}}-CH_2-CH_3 \xrightarrow[140^\circ C]{H_2SO_4}$$

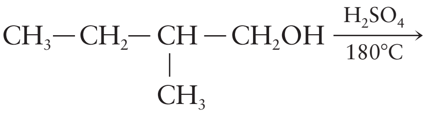
13.38 Draw the structure of the product expected when each of the following alcohols is reacted with a sulfuric acid catalyst at the temperature indicated.

a.



$$CH_3-\underset{OH}{\underset{|}{CH}}CH_2CH_3 \xrightarrow[180^\circ C]{H_2SO_4}$$

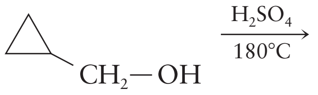
b.



$$CH_3-CH_2-\underset{CH_3}{\underset{|}{CH}}-CH_2OH \xrightarrow[180^\circ C]{H_2SO_4}$$

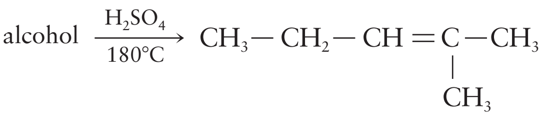
c. $CH_3-CH_2-CH_2-OH \xrightarrow[140^\circ C]{H_2SO_4}$

d.



13.39 Draw the structural formula of the alcohol that will make the following products through an alcohol dehydration reaction.

a.

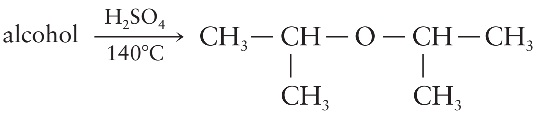


$$\text{alcohol} \xrightarrow[180^\circ C]{H_2SO_4} CH_3-CH_2-CH=\underset{CH_3}{\underset{|}{C}}-CH_3$$

b. alcohol $\xrightarrow[180^\circ C]{H_2SO_4} CH_3-CH_2-CH=CH_2$

c. alcohol $\xrightarrow[140^\circ C]{H_2SO_4} CH_3-CH_2-O-CH_2-CH_3$

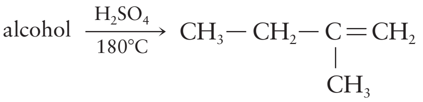
d.



$$\text{alcohol} \xrightarrow[140^\circ C]{H_2SO_4} CH_3-\underset{CH_3}{\underset{|}{CH}}-O-\underset{CH_3}{\underset{|}{CH}}-CH_3$$

13.40 Draw the structural formula of the alcohol that will make the following products through an alcohol dehydration reaction.

a.

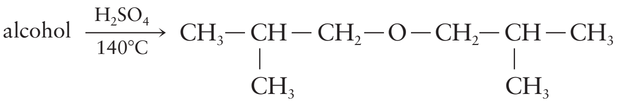


$$\text{alcohol} \xrightarrow[180^\circ C]{H_2SO_4} CH_3-CH_2-\underset{CH_3}{\underset{|}{C}}=CH_2$$

b. alcohol $\xrightarrow[180^\circ C]{H_2SO_4} CH_3-CH=CH_2$

c. alcohol $\xrightarrow[140^\circ C]{H_2SO_4} CH_3-O-CH_3$

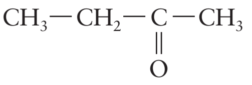
d.



$$\text{alcohol} \xrightarrow[140^\circ C]{H_2SO_4} CH_3-\underset{CH_3}{\underset{|}{CH}}-CH_2-O-CH_2-\underset{CH_3}{\underset{|}{CH}}-CH_3$$

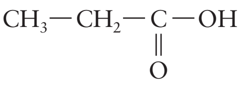
13.41 Identify whether a primary or secondary alcohol was oxidized to make each of the following compounds.

a.



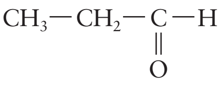
$$CH_3-CH_2-\underset{O}{\underset{\|}{C}}-CH_3$$

b.



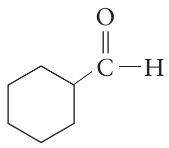
$$CH_3-CH_2-\underset{O}{\underset{\|}{C}}-OH$$

c.



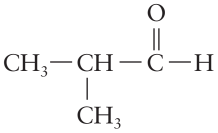
$$CH_3-CH_2-\underset{O}{\underset{\|}{C}}-H$$

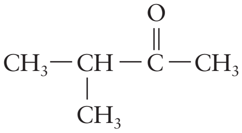
d.

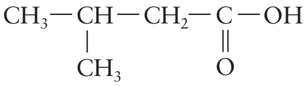


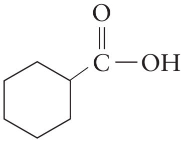
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

13.42 Identify whether a primary or secondary alcohol was oxidized to make each of the following compounds.

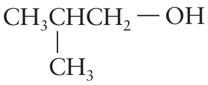
a. 
$CH_3-\underset{\displaystyle CH_3}{\underset{|}{CH}}-\overset{\displaystyle O}{\overset{\|}{C}}-H$

b. 
$CH_3-\underset{\displaystyle CH_3}{\underset{|}{CH}}-\overset{\displaystyle O}{\overset{\|}{C}}-CH_3$

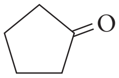
c. 
$CH_3-\underset{\displaystyle CH_3}{\underset{|}{CH}}-CH_2-\underset{\displaystyle O}{\underset{\|}{C}}-OH$

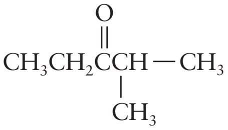
d. 

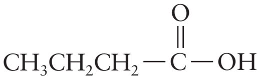
13.43 Draw the structures of the two organic compounds that can be obtained by oxidizing


$CH_3\underset{\displaystyle CH_3}{\underset{|}{C}}HCH_2-OH$

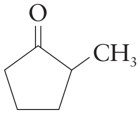
13.44 Give the structure of an alcohol that could be used to prepare each of the following compounds:

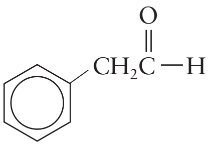
a. 

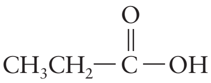
b. 
$CH_3CH_2\overset{\displaystyle O}{\overset{\|}{C}}\underset{\displaystyle CH_3}{\underset{|}{CH}}-CH_3$

c. 
$CH_3CH_2CH_2-\overset{\displaystyle O}{\overset{\|}{C}}-OH$

13.45 Give the structure of an alcohol that could be used to prepare each of the following compounds:

a. 

b. 

c. 
$CH_3CH_2-\overset{\displaystyle O}{\overset{\|}{C}}-OH$

13.46 What products would result from the following processes? Write an equation for each reaction.

a. 2-Methyl-2-butanol is subjected to controlled oxidation.

b. 1-Propanol is heated to 140°C in the presence of sulfuric acid.

c. 3-Pentanol is subjected to controlled oxidation.

d. 3-Pentanol is heated to 180°C in the presence of sulfuric acid.

e. 1-Hexanol is subjected to an *excess* of oxidizing agent.

13.47 What products would result from the following processes? Write an equation for each reaction.

a. 1-Butanol is heated to 140°C in the presence of sulfuric acid.

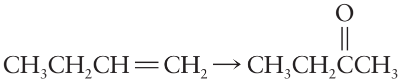
b. 1-Butanol is subjected to an *excess* of oxidizing agent.

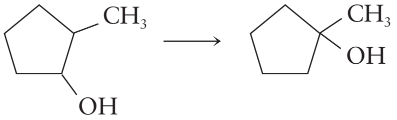
c. 2-Pentanol is subjected to controlled oxidation.

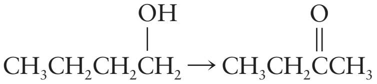
d. 2-Pentanol is heated to 180°C in the presence of sulfuric acid.

e. 2-Methyl-2-pentanol is subjected to controlled oxidation.

13.48* Each of the following conversions requires more than one step, and some reactions studied in previous chapters may be needed. Show the reagents you would use and draw structural formulas for intermediate compounds formed in each conversion.

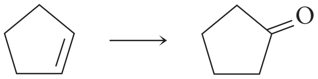
a. 
$CH_3CH_2CH=CH_2 \rightarrow CH_3CH_2\overset{\displaystyle O}{\overset{\|}{C}}CH_3$

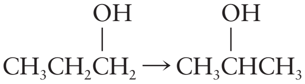
b. 

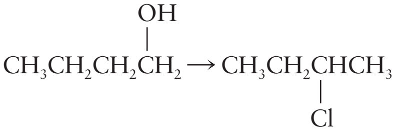
c. 
$CH_3CH_2CH_2\overset{\displaystyle OH}{\overset{|}{C}}H_2 \rightarrow CH_3CH_2\overset{\displaystyle O}{\overset{\|}{C}}CH_3$

13.49* Each of the following conversions requires more than one step, and some reactions studied in previous chapters may be needed. Show the reagents you would use and draw structural formulas for intermediate compounds formed in each conversion.

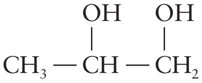
a. $CH_2=CH_2 \rightarrow CH_3CH_2-O-CH_2CH_3$

b. 

c. 
$CH_3CH_2\overset{\displaystyle OH}{\overset{|}{C}}H_2 \rightarrow CH_3\overset{\displaystyle OH}{\overset{|}{C}}HCH_3$

d. 
$CH_3CH_2CH_2\overset{\displaystyle OH}{\overset{|}{C}}H_2 \rightarrow CH_3CH_2\underset{\displaystyle Cl}{\underset{|}{C}}HCH_3$

13.50 The three-carbon diol used in antifreeze is


$CH_3-\overset{\displaystyle OH}{\overset{|}{CH}}-\overset{\displaystyle OH}{\overset{|}{CH_2}}$

It is nontoxic and is used as a moisturizing agent in foods. Oxidation of this substance within the liver produces pyruvic acid, which can be used by the body to supply energy. Give the structure of pyruvic acid.

Important Alcohols (Section 13.5)

13.51 Methanol is fairly volatile and evaporates quickly if spilled. Methanol is also absorbed quite readily through the skin. If, in the laboratory, methanol accidentally spilled on your clothing, why would it be a serious mistake to just let it evaporate?

13.52 Why is methanol such an important industrial chemical?

13.53 Suppose you are making some chocolate cordials (chocolate-coated candies with soft fruit filling). Why might you want to add a little glycerol to the filling?

13.54 Name an alcohol used in each of the following ways:

- **a.** A moistening agent in many cosmetics
- **b.** A solvent in solutions called tinctures
- **c.** Automobile antifreeze
- **d.** Rubbing alcohol

13.55 Name an alcohol used in each of the following ways:

- **a.** A flavoring in cough drops
- **b.** Present in gasohol
- **c.** Active ingredient in alcoholic beverages
- **d.** Industrially produced from CO and H_2

Characteristics and Uses of Phenols (Section 13.6)

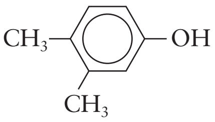
13.56 Name a phenol associated with each of the following:

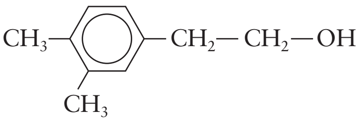
- **a.** A vitamin
- **b.** A disinfectant cleaner

13.57 Name a phenol used in each of the following ways:

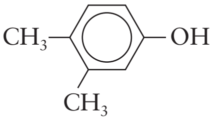
- **a.** A disinfectant used for cleaning walls
- **b.** An antiseptic found in some mouthwashes
- **c.** An antioxidant used to prevent rancidity in foods

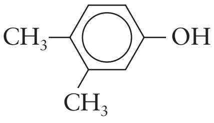
13.58 Explain why the first of the following two compounds is a phenol, and the second is not.





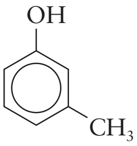
13.59 Explain why the first of the following two compounds is a phenol, and the second is not.



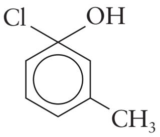


13.60 Which of the molecular structures below cannot possibly exist in nature? Explain why not.

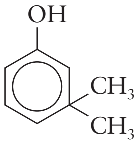
a.



b.

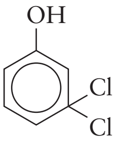


c.

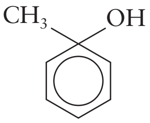


13.61 Which of the molecular structures below cannot possibly exist in nature? Explain why not.

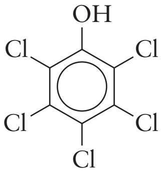
a.



b.



c.

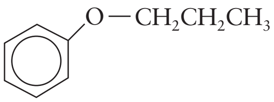


Ethers (Section 13.7)

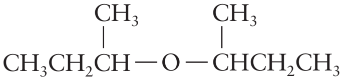
13.62 Assign a common name to each of the following ethers:

a. $CH_3—O—CH_2CH_3$

b.



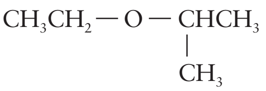
c.



$$\begin{array}{c} \quad CH_3 \qquad\quad CH_3 \\ \quad | \qquad\qquad | \\ CH_3CH_2CH—O—CHCH_2CH_3 \end{array}$$

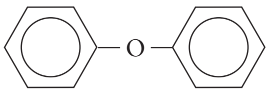
13.63 Assign a common name to each of the following ethers:

a.



$$\begin{array}{l} CH_3CH_2—O—CHCH_3 \\ \qquad\qquad\qquad\;\; | \\ \qquad\qquad\qquad CH_3 \end{array}$$

c.



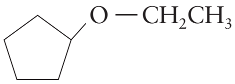
b. $CH_3—O—CH_2CH_2CH_2CH_3$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

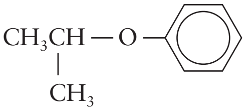
13.64 Assign the IUPAC name to each of the following ethers. Name the smaller alkyl group as the alkoxy group.

a. $CH_3-O-CH_2CH_3$

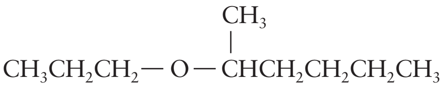
b.



c.



d.

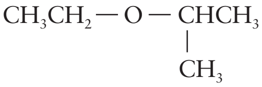


$CH_3CH_2CH_2-O-\overset{\overset{CH_3}{|}}{C}HCH_2CH_2CH_2CH_3$

13.65 Assign the IUPAC name to each of the following ethers. Name the smaller alkyl group as the alkoxy group.

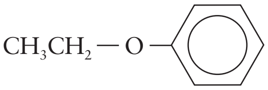
a. $CH_3CH_2-O-CH_2CH_2CH_3$

b.

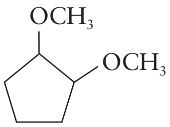


$CH_3CH_2-O-\underset{\underset{CH_3}{|}}{C}HCH_3$

c.



d.



13.66 Draw structural formulas for the following:

a. ethyl methyl ether

b. butyl phenyl ether

c. 3-ethoxypentane

d. dipropyl ether

e. 1,3-dipropoxycyclohexane

13.67 Draw structural formulas for the following:

a. methyl isopropyl ether

b. phenyl propyl ether

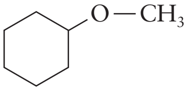
c. 2-methoxypentane

d. 1,2-diethoxycyclopentane

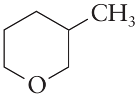
e. 2-phenoxy-2-butene

13.68 Identify each of the following molecular structures as that of a heterocyclic ring ether, a noncyclic ring ether, or a nonether.

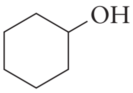
a.



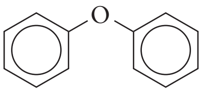
b.



c.

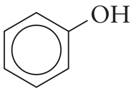


d.

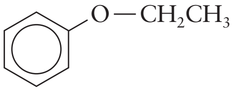


13.69 Identify each of the following molecular structures as that of a heterocyclic ring ether, a noncyclic ring ether, or a nonether.

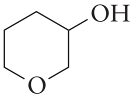
a.



b.



c.



d. $CH_3CH_2-O-CH_2CH_3$

13.70 Give the IUPAC names and draw structural formulas for the three isomeric ethers of the molecular formula $C_4H_{10}O$.

13.71 Give the IUPAC names and draw structural formulas for the six isomeric ethers of the molecular formula $C_5H_{12}O$.

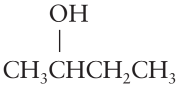
Properties of Ethers (Section 13.8)

13.72 What is the chief chemical property of ethers?

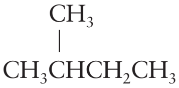
13.73 Why is diethyl ether hazardous to use as an anesthetic or as a solvent in the laboratory?

13.74 Arrange the following compounds in order of decreasing solubility in water. Explain the basis for your decision.

$CH_3CH_2-O-CH_2CH_3$



$CH_3\overset{\overset{OH}{|}}{C}HCH_2CH_3$



$CH_3\overset{\overset{CH_3}{|}}{C}HCH_2CH_3$

13.75 Arrange the following compounds in order of decreasing solubility in water. Explain the basis for your decisions.

13.76 Arrange the compounds in Exercise 13.74 in order of decreasing boiling point. Explain your answer.

$CH_3CH_2CH_2-OH \quad CH_3CH_2CH_2CH_3 \quad CH_3CH_2-O-CH_3$

13.77 Arrange the compounds in Exercise 13.75 in order of decreasing boiling point. Explain your answer.

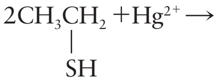
13.78 Draw structural formulas and use a dotted line to show hydrogen bonding between a molecule of methoxyethane and water.

13.79 Draw structural formulas and use a dotted line to show hydrogen bonding between a molecule of diethyl ether and water.

Thiols (Section 13.9)

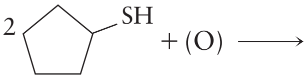
13.80 Complete the following reactions:

a.



$2CH_3\underset{\underset{SH}{|}}{CH_2} + Hg^{2+} \rightarrow$

b.



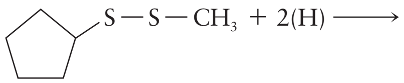
c. $CH_3-S-S-CH_2CH_2CH_3 + 2(H) \rightarrow$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

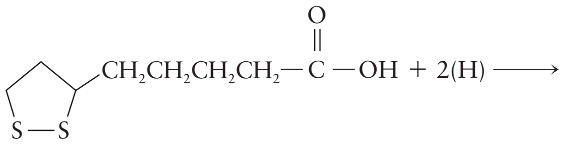
13.81 Complete the following reactions:

a. $2CH_3CH_2CH_2{-}SH + Hg^{2+} \rightarrow$

b. $2CH_3CH_2CH_2{-}SH + (O) \rightarrow$

c. 

13.82 Lipoic acid is required by many microorganisms for proper growth. As a disulfide, it functions in the living system by catalyzing certain oxidation reactions and is reduced in the process. Write the structure of the reduction product.

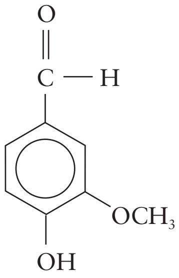


lipoic acid

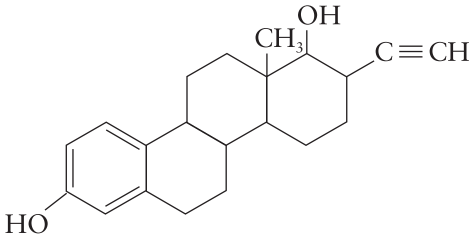
13.83 Alcohols and thiols can both be oxidized in a controlled way. What are the differences in the products?

Polyfunctional Compounds (Section 13.10)

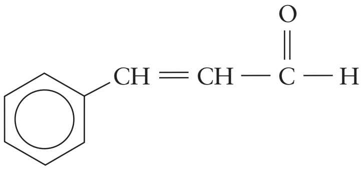
13.84 Identify the functional groups in vanillin, the active ingredient in vanilla flavoring.



13.85 Ethynlestradiol acts as an estrogen (the primary female sex hormone) and has been used in contraceptives. Identify the functional groups in this compound.



13.86 Identify the functional groups in cinnamaldehyde, present in cinnamon flavoring.



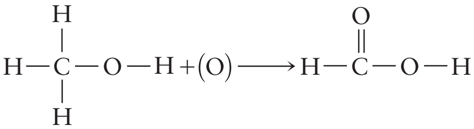
Additional Exercises

13.87 alkene + water $\xrightleftharpoons{H_2SO_4}$ alcohol + heat

In simplistic terms, it can be thought that an equilibrium exists in the hydration-dehydration reactions above. Use LeChâtelier's principle to explain why the dehydration reaction is favored at 180°C.

13.88 Thiols have lower boiling points and are less water soluble than the corresponding alcohol (e.g., $CH_3CH_2{-}OH$ and $CH_3CH_2{-}SH$). Explain why.

13.89 The internal oxidation of methanol yields methanoic acid, a highly toxic compound which can result in blindness, coma, and death. Determine the oxidation numbers on the carbon atom in the following reaction.



$$H{-}\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{C}}}}{-}O{-}H + (O) \longrightarrow H{-}\overset{\displaystyle O}{\overset{\|}{C}}{-}O{-}H$$

methanol methanoic acid

13.90 Because of the acidity of phenol, handling the compound can result in chemical burns. Using the idea of aromaticity (the electronic structure of benzene), explain why phenol is a stronger acid than cyclohexanol.

13.91 In **Section 13.6**, the structure of 4-hexylresorcinol, a common component in throat lozenges, is shown. Give another name for 4-hexylresorcinol using the ending -diol.

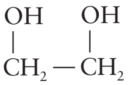
13.92 Use general reactions to show how an alcohol (R—O—H) can behave as a weak Brønsted acid when it reacts with a strong Brønsted base (X^-). Next, show how an alcohol can behave as a weak Brønsted base in the presence of a strong Brønsted acid (HA).

Chemistry for Thought

13.93 Many aftershaves are 50% ethanol. What do you think is the purpose of the ethanol?

13.94 A mixture of ethanol and 1-propanol is heated to 140°C in the presence of sulfuric acid. Careful analysis reveals that three ethers are formed. Write formulas for these three products, name each, and explain why three form, rather than a single product.

13.95 The two-carbon alcohol in some antifreeze



$$\overset{\displaystyle OH}{\overset{|}{CH_2}}{-}\overset{\displaystyle OH}{\overset{|}{CH_2}}$$

is toxic if ingested. Reactions within the liver oxidize the diol to oxalic acid, which can form insoluble salts and damage the kidneys. Give the structure of oxalic acid.

13.96 Although ethanol is only mildly toxic to adults, it poses greater risks for fetuses. Why do you think this is the case?

13.97 The medicinal compound taxol is mentioned in **Figure 13.1**. What does the name indicate about its possible structure?

13.98 Norgesterone acts as a progestin (a hormone that regulates the menstrual cycle). What does the name indicate about its possible structure?

13.99 When diethyl ether is spilled on the skin, the skin takes on a dry appearance. Explain whether this effect is more likely due to a removal of water or a removal of natural skin oils.

13.100 **Figure 13.12** points out that methanol is used as a fuel in racing cars. Write a balanced equation for the combustion of methanol.

13.101 **Figure 13.19** focuses on the use of thiol chemistry by skunks. If thiols are more volatile than alcohols and less soluble in water, why do these properties represent an advantage to skunks?

13.102 Why do you think a dye is added to antifreeze before it is sold in stores?

13.103 Glycerol, or glycerin, is used as a moisturizer in foods such as candy and shredded coconut. What is the molecular explanation for its utility as a moisturizer?

14 Aldehydes and Ketones

iStock.com/shapecharge

Health Career Focus

NURSE PRACTITIONER

It's the best of both worlds. I get to practice nursing with an emphasis on holistic patient care—different from the typical doctor—yet I also get to diagnose and prescribe medications. I make decisions in ways that I couldn't as an RN. At the same time, I work under the supervision of an M.D., so I'm not on my own. I don't carry all that responsibility. If I'm not sure of something, I can always consult my doctor partner.

As a nurse practitioner, I'm able to specialize. I earned a certificate in prescribing psychotropic medications. As the stigma against mental health treatment diminishes, there's a growing need for care. Now, more people seek treatment for anxiety, depression, and Attention Deficit Hypersensitivity Disorder (ADHD); and psychologist's waiting lists are long. I fill a gap in the health care system. I meet people at a level of care where they need help but may not require a doctor to meet their needs.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

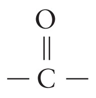
Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Recognize the carbonyl group in compounds and classify the compounds as aldehydes or ketones. **(Section 14.1)**
2. Assign IUPAC names to aldehydes and ketones. **(Section 14.1)**
3. Compare the physical properties of aldehydes and ketones with those of compounds in other classes. **(Section 14.2)**
4. Write key reactions for aldehydes and ketones. **(Section 14.3)**
5. Give specific uses for aldehydes and ketones. **(Section 14.4)**

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

THE CARBONYL FUNCTIONAL GROUP is characteristic of both aldehydes and ketones. In a **carbonyl group**, a carbon is double bonded to an oxygen atom and single bonded to two other atoms:

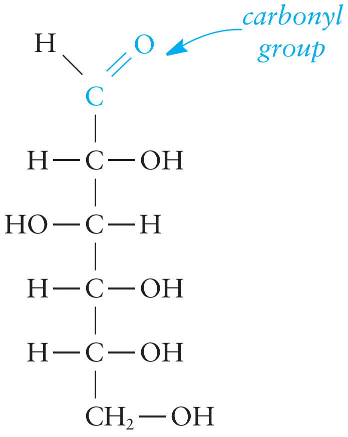


$$-\overset{O}{\overset{\|}{C}}-$$

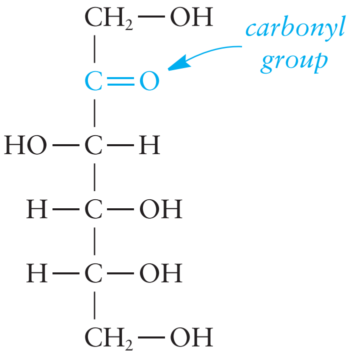
carbonyl group

carbonyl group
The $-\overset{O}{\overset{\|}{C}}-$ group.

Aldehydes and ketones occur widely in nature and play important roles in living organisms. For example, the carbonyl group is found in numerous carbohydrates, including glucose and fructose. Glucose, a major source of energy in living systems, is found combined with fructose in cane sugar:



glucose



fructose

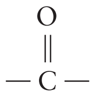
In this chapter, we will study the naming of aldehydes and ketones, as well as some of their important reactions. These concepts will be very useful when we study the chemistry of carbohydrates in **Chapter 17**.

14.1 The Nomenclature of Aldehydes and Ketones

Learning Objective 1 Recognize the carbonyl group in compounds and classify the compounds as aldehydes or ketones.

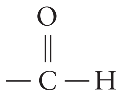
Learning Objective 2 Assign IUPAC names to aldehydes and ketones.

When a carbonyl group is directly bonded to at least one hydrogen atom, the compound is an **aldehyde**. In **ketones**, two carbon atoms are directly bonded to the carbonyl group:



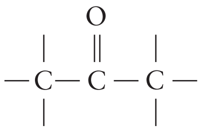
$$-\overset{O}{\overset{\|}{C}}-$$

carbonyl group



$$-\overset{O}{\overset{\|}{C}}-H$$

aldehyde



$$-\overset{|}{\underset{|}{C}}-\overset{O}{\overset{\|}{C}}-\overset{|}{\underset{|}{C}}-$$

ketone

aldehyde
A compound that contains the $-\overset{O}{\overset{\|}{C}}-H$ group; the general formula is $R-\overset{O}{\overset{\|}{C}}-H$.

ketone
A compound that contains the $-\overset{|}{\underset{|}{C}}-\overset{O}{\overset{\|}{C}}-\overset{|}{\underset{|}{C}}-$ group; the general formula is $R-\overset{O}{\overset{\|}{C}}-R'$.

Structural models of the simplest aldehyde (formaldehyde) and the simplest ketone (acetone) are shown in **Figure 14.1**.

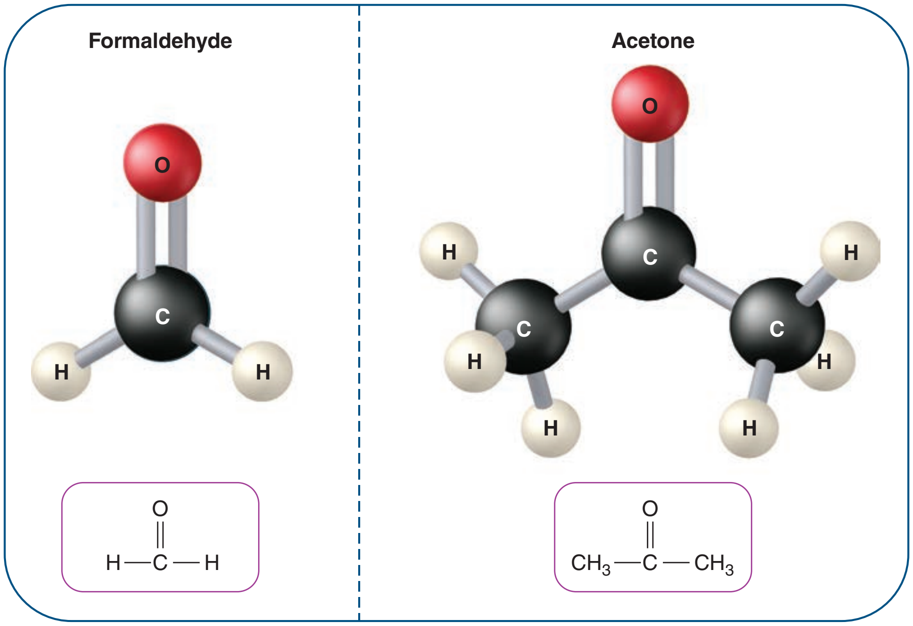


FIGURE 14.1 Ball-and-stick models of formaldehyde and acetone.

iStock.com/redmal

FIGURE 14.2 Formaldehyde is used to preserve biological specimens.

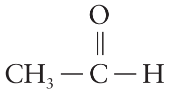
Several aldehydes and ketones, in addition to formaldehyde (see **Figure 14.2**) and acetone, are well known by common names (see **Table 14.1**). Notice that aldehyde and ketone common names are easily recognized by the endings *-aldehyde* and *-one*, respectively.

In the IUPAC system, aldehydes are named by selecting the longest chain that includes the carbonyl carbon. The *-e* of the alkane that has the same number of carbons is replaced by *-al*. Because the carbonyl carbon in aldehydes is always at the end of the chain, it is always designated as carbon number 1.

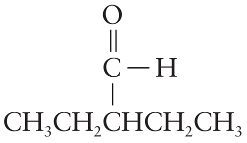
Example 14.1 Naming Aldehydes

The common name for the two-carbon aldehyde, shown in part a, is acetaldehyde. It is a toxic substance produced when alcohol is broken down in the liver.

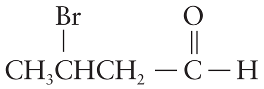
Name the following aldehydes according to the IUPAC system.

a.


$$CH_3-\overset{\overset{O}{\|}}{C}-H$$

c.


$$CH_3CH_2\overset{\overset{\overset{O}{\|}}{C}-H}{\overset{|}{C}}HCH_2CH_3$$

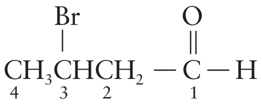
b.


$$CH_3\overset{\overset{Br}{|}}{C}HCH_2-\overset{\overset{O}{\|}}{C}-H$$

Solution

a. This aldehyde contains two carbon atoms, and the name is ethanal. The aldehyde group is always position number 1, so the number designating the aldehyde position is omitted from the name.

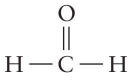
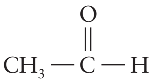
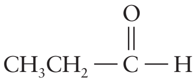
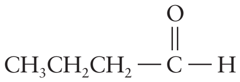
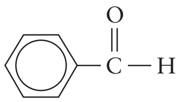
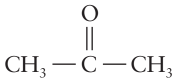
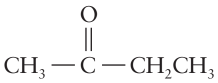
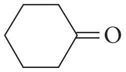
b. Carbon chain numbering begins with the carbonyl end of the molecule even though a lower number for the Br could be obtained by numbering from the left:



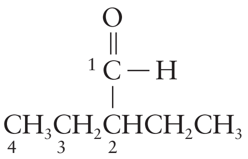
$$\underset{4}{CH_3}\overset{\overset{Br}{|}}{\underset{3}{C}}H\underset{2}{CH_2}-\overset{\overset{O}{\|}}{\underset{1}{C}}-H$$

The compound is 3-bromobutanal.

TABLE 14.1 Some Common Aldehydes and Ketones

Structural Formula	IUPAC Name	Common Name	Boiling Point (°C)
Aldehydes			
 $H-\overset{\overset{O}{\|}}{C}-H$	methanal	formaldehyde	−21
 $CH_3-\overset{\overset{O}{\|}}{C}-H$	ethanal	acetaldehyde	21
 $CH_3CH_2-\overset{\overset{O}{\|}}{C}-H$	propanal	propionaldehyde	49
 $CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-H$	butanal	butyraldehyde	76
	benzaldehyde	benzaldehyde	178
Ketones			
 $CH_3-\overset{\overset{O}{\|}}{C}-CH_3$	propanone	acetone	56
 $CH_3-\overset{\overset{O}{\|}}{C}-CH_2CH_3$	butanone	methyl ethyl ketone (MEK)	80
	cyclohexanone	cyclohexanone	156

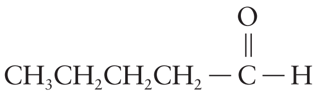
c. The carbonyl group must be position number 1 in the chain even though a longer carbon chain (pentane) exists:

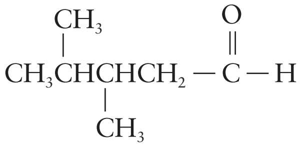


$$\begin{array}{c} O \\ \| \\ {}^{1}C-H \\ | \\ \underset{4}{CH_3}\underset{3}{CH_2}\underset{2}{CH}CH_2CH_3 \end{array}$$

The name is 2-ethylbutanal.

✔ LEARNING CHECK 14.1 Give IUPAC names to the following aldehydes:

a.  $CH_3CH_2CH_2CH_2-\overset{\overset{O}{\|}}{C}-H$

b.  $CH_3\overset{\overset{CH_3}{|}}{C}H\underset{\underset{CH_3}{|}}{C}HCH_2-\overset{\overset{O}{\|}}{C}-H$

iStock.com/bhofack2

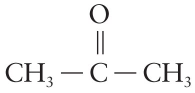
FIGURE 14.3 The ending *-dione* in butanedione correctly implies there are two ketone groups in its structure. Butanedione gives rise to the pleasant odor of melted butter.

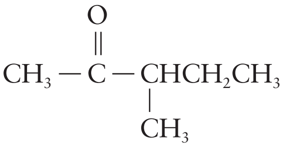
In naming ketones by the IUPAC system, the longest chain that includes the carbonyl group is given the name of the corresponding alkane, with the *-e* replaced by *-one* (see **Figure 14.3**). The chain is numbered from the end closest to the carbonyl group, and the carbonyl group position is indicated by a number.

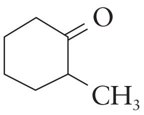
Example 14.2 Naming Ketones

Acetone, the common name for the compound shown in part a, is produced by the body during carbohydrate restrictive diets and starvation.

Give IUPAC names to the following ketones:

a. 
$CH_3-\overset{O}{\overset{\|}{C}}-CH_3$

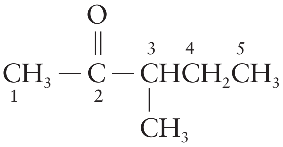
b. 
$CH_3-\overset{O}{\overset{\|}{C}}-\underset{\underset{CH_3}{|}}{C}HCH_2CH_3$

c. 

Solution

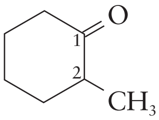
a. There are three carbons in the chain, and the correct name is propanone. The number 2 is not used in this case because the carbonyl group in a ketone cannot be on the end of a chain. Therefore, it must be in the number 2 position.

b. The chain is numbered from the left to give a lower number for the carbonyl carbon:


$\underset{1}{CH_3}-\underset{2}{\overset{O}{\overset{\|}{C}}}-\overset{3}{\underset{\underset{CH_3}{|}}{C}}H\overset{4}{C}H_2\overset{5}{C}H_3$

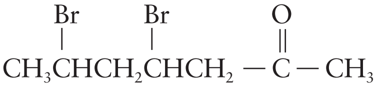
The complete name is 3-methyl-2-pentanone.

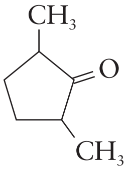
c. In cyclic ketones, the carbonyl carbon will always be at position 1, and so the number is omitted from the name:



The correct name is 2-methylcyclohexanone.

✔ **LEARNING CHECK 14.2** Give IUPAC names to the following ketones:

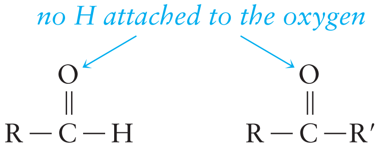
a. 
$CH_3\overset{Br}{\overset{|}{C}}HCH_2\overset{Br}{\overset{|}{C}}HCH_2-\overset{O}{\overset{\|}{C}}-CH_3$

b. 

14.2 Physical Properties

Learning Objective 3 Compare the physical properties of aldehydes and ketones with those of compounds in other classes.

The physical properties of aldehydes and ketones can be explained by an examination of their structures. First, the lack of a hydrogen on the oxygen prevents the formation of hydrogen bonds between molecules:



$R-\overset{O}{\overset{\|}{C}}-H \qquad R-\overset{O}{\overset{\|}{C}}-R'$

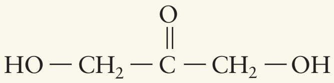
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS **14.1**

Faking a Tan

Many people believe that a suntan makes one look healthy and attractive. Studies, however, indicate that this perception is far from the truth. According to these studies, sunbathing, especially when sunburn results, ages the skin prematurely and increases the risk of skin cancer. Cosmetic companies have developed a tanning alternative for those not willing to risk using the sun but who want to be "fashionably" tan.

Tanning lotions and creams that chemically darken the skin are now available. The active ingredient in these "bronzers" is dihydroxyacetone (DHA), a colorless compound classified by the Food and Drug Administration as a safe skin dye.



$$HO-CH_2-\overset{O}{\overset{\|}{C}}-CH_2-OH$$

dihydroxyacetone (DHA)

Within several hours after application, DHA produces a brown skin color by reacting with the outer layer of the skin, which consists of dead cells. Only the dead cells react with DHA, so the color gradually fades as the dead cells slough off and are replaced. This process generally leads to the fading of chemical tans within a few weeks. Another problem with chemical tans is uneven skin color. Areas of skin such as elbows and knees, which contain a thicker layer of dead cells, may absorb and react with more tanning lotion and become darker than other areas.

Perhaps the greatest problem with chemical tans is the false sense of security they might give. Some people with chemical tans think it is safe to go into the sun and get a deeper tan. This isn't true. Sunlight presents the same hazards to chemically tanned skin that it does to untanned skin.

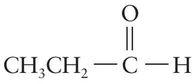
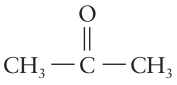
Neutrogena
Sunless Tanning
SPRAY
LIGHT MEDIUM
Coppertone
Sunless
TANNER LOTION
LIGHT/MEDIUM
BANANA BOAT
Sunless
Deep Dark Blend
Self Adjusting Color
BANANA BOAT
SUNLESS
TANNING SPRAY
Self Adjusting Color
NON-AEROSOL

© Maren Slabaugh

Some DHA-containing products.

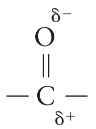
Therefore, boiling points of pure aldehydes and ketones are expected to be lower than those of alcohols with similar molecular weights. Remember, alcohols can form hydrogen bonds with one another. **Table 14.2** shows that the boiling points of propanal and acetone are 49°C and 56°C, respectively, whereas the alcohol of comparable molecular weight, 1-propanol, has a boiling point of 97°C.

TABLE 14.2 A Comparison of Physical Properties

Class	Example	Formula	Molecular weight	Boiling point (°C)	Water solubility
Alkane	butane	$CH_3CH_2CH_2CH_3$	58	0	Insoluble
Aldehyde	propanal	 $CH_3CH_2-\overset{O}{\overset{\|}{C}}-H$	58	49	Soluble
Ketone	propanone (acetone)	 $CH_3-\overset{O}{\overset{\|}{C}}-CH_3$	58	56	Soluble
Alcohol	1-propanol	$CH_3CH_2CH_2-OH$	60	97	Soluble

Also notice in **Table 14.2** that the boiling points of the aldehyde and ketone are higher than that of the comparable alkane. This can be explained by differences in polarity.

Whereas alkanes are nonpolar, the carbonyl group of aldehydes and ketones is polar due to the more electronegative oxygen atom:



The attractive forces between molecules possessing such dipoles are not as strong as hydrogen bonds, but they do cause aldehydes and ketones to boil at higher temperatures than the nonpolar alkanes. The graph in **Figure 14.4** summarizes the boiling point comparison for several families of compounds.

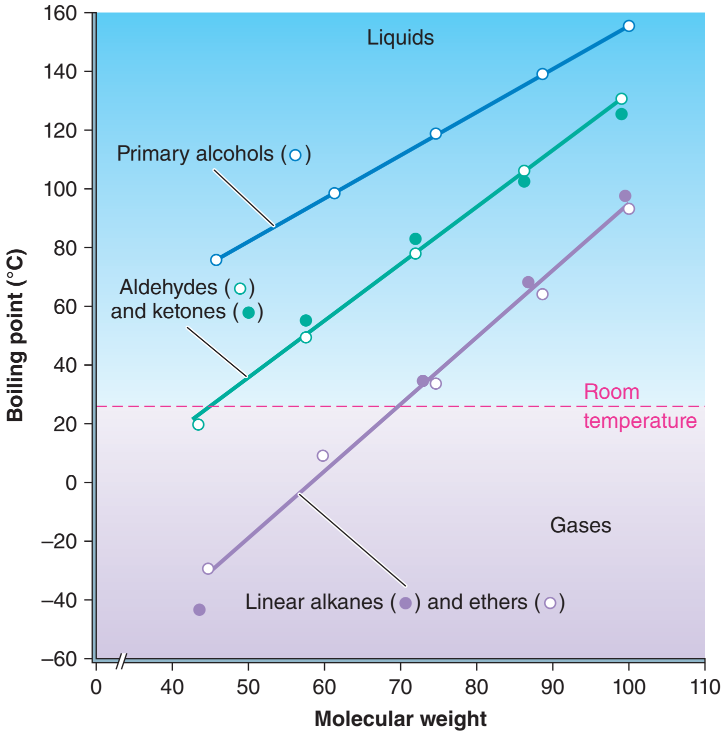
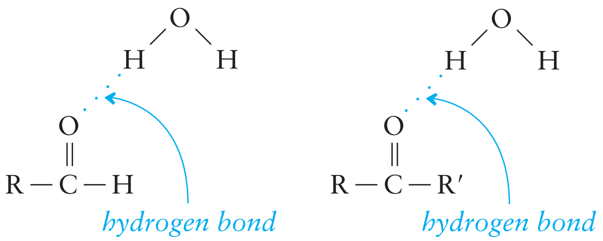


FIGURE 14.4 The boiling points of aldehydes and ketones are higher than those of alkanes and ethers but lower than those of alcohols of comparable molecular weights.

Water is a polar solvent and would be expected to be effective in dissolving compounds containing polar carbonyl groups. Besides exhibiting dipolar attractions, the carbonyl oxygen also forms hydrogen bonds with water:



As a result, low molecular weight aldehydes and ketones are water soluble (see **Table 14.2**).

14.3 Chemical Properties

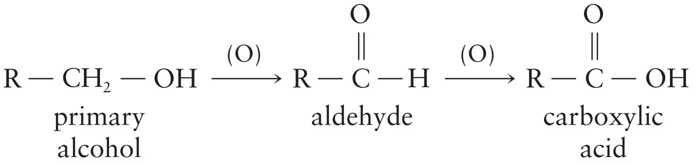
Learning Objective 4 Write key reactions for aldehydes and ketones.

14.3A Oxidation

We learned in **Section 13.4** that when aldehydes are prepared by oxidizing primary alcohols with $KMnO_4$ or $K_2Cr_2O_7$, the reaction may continue and produce carboxylic acids.

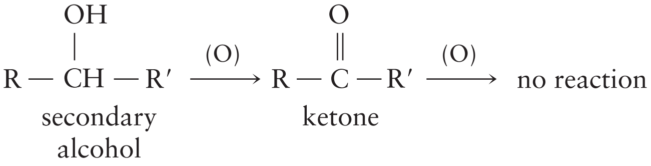
Ketones are prepared similarly, but they are much less susceptible to further oxidation, especially by mild oxidizing agents:

General reaction:



$$\underset{\text{primary alcohol}}{R-CH_2-OH} \xrightarrow{(O)} \underset{\text{aldehyde}}{R-\overset{\overset{\Large O}{\|}}{C}-H} \xrightarrow{(O)} \underset{\text{carboxylic acid}}{R-\overset{\overset{\Large O}{\|}}{C}-OH} \quad (14.1)$$

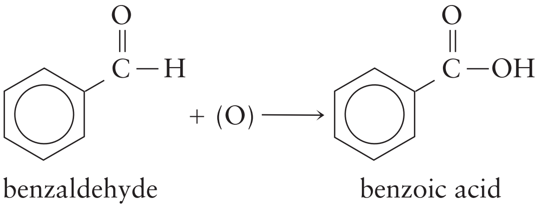
General reaction:



$$\underset{\text{secondary alcohol}}{R-\overset{\overset{\Large OH}{|}}{CH}-R'} \xrightarrow{(O)} \underset{\text{ketone}}{R-\overset{\overset{\Large O}{\|}}{C}-R'} \xrightarrow{(O)} \text{no reaction} \quad (14.2)$$

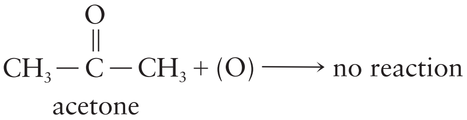
The difference in reactivity toward oxidation is the chief reason why aldehydes and ketones are classified in separate families (see **Figure 14.5**).

Specific example:

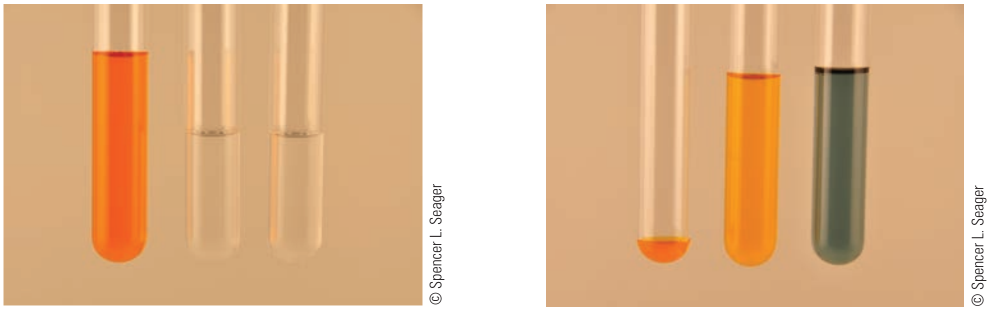


(14.3)

Specific example:



$$\underset{\text{acetone}}{CH_3-\overset{\overset{\Large O}{\|}}{C}-CH_3} + (O) \longrightarrow \text{no reaction} \quad (14.4)$$



© Spencer L. Seager

© Spencer L. Seager

1 From left to right, three test tubes containing potassium dichromate ($K_2Cr_2O_7$), acetone, and benzaldehyde.

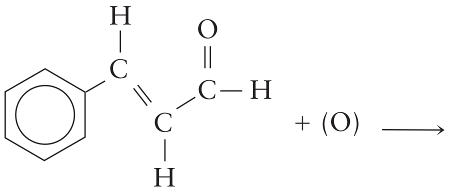
2 After the addition of equal amounts of $K_2Cr_2O_7$ from the first test tube, the acetone remains unreacted, whereas the benzaldehyde is oxidized.

FIGURE 14.5 Attempted oxidation of acetone and oxidation of benzaldehyde. As the reaction proceeds, chromium is reduced, forming a grayish green precipitate.

The oxidation of aldehydes occurs so readily that even atmospheric oxygen causes the reaction. A few drops of liquid benzaldehyde (Reaction 14.3) placed on a watch glass will begin to oxidize to solid benzoic acid within an hour. In the laboratory, it is not unusual to find that bottles of aldehydes that have been opened for a length of time contain considerable amounts of carboxylic acids.

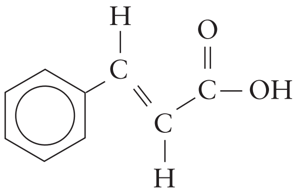
Example 14.3 Writing Oxidation Reactions

Cinnamaldehyde is the compound that gives cinnamon its characteristic aroma and taste. Draw the structural formula for the oxidation product of cinnamaldehyde.



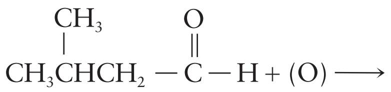
Solution

This reaction is similar to Key Reaction 14.1, in which an aldehyde is oxidized to a carboxylic acid.



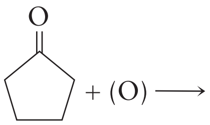
✔ LEARNING CHECK 14.3 Draw the structural formula for each product. Write "no reaction" if none occurs.

a.



$$\mathrm{CH_3\overset{\overset{\displaystyle CH_3}{|}}{C}HCH_2-\overset{\overset{\displaystyle O}{\|}}{C}-H+(O)\longrightarrow}$$

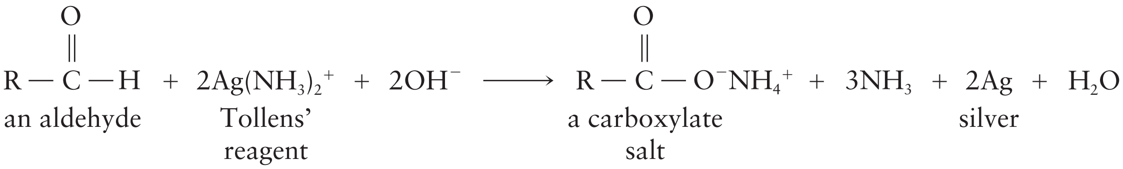
b.



The effectiveness of two common chemical reagents used to test for the presence of aldehydes—Tollens' reagent and Benedict's reagent—depends on the ease with which aldehydes are oxidized. In general, ketones fail to react with these same reagents.

Tollens' reagent A mild oxidizing solution containing silver ions used to test for aldehydes.

Tollens' reagent is a mild oxidizing solution containing complexed Ag^+ ions. The oxidizing agent is the silver ion, which is reduced to metallic silver in the process and precipitates out (Reaction 14.5):



$$\underset{\text{an aldehyde}}{\mathrm{R-\overset{\overset{\displaystyle O}{\|}}{C}-H}} + \underset{\substack{\text{Tollens'}\\ \text{reagent}}}{2\mathrm{Ag(NH_3)_2}^+} + 2\mathrm{OH}^- \longrightarrow \underset{\substack{\text{a carboxylate}\\ \text{salt}}}{\mathrm{R-\overset{\overset{\displaystyle O}{\|}}{C}-O^-NH_4^+}} + 3\mathrm{NH_3} + \underset{\text{silver}}{2\mathrm{Ag}} + \mathrm{H_2O} \qquad (14.5)$$

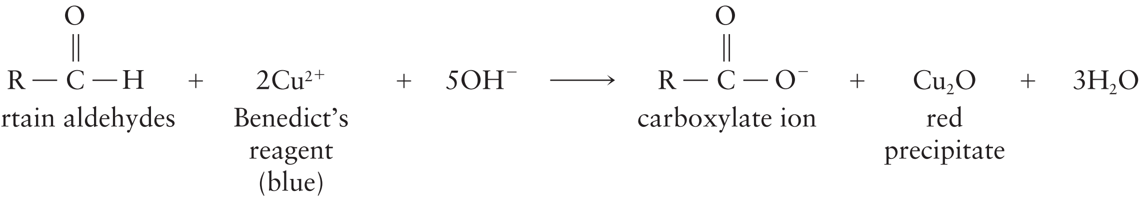
When the reaction is carried out in a clean, grease-free glass container, the metallic silver deposits on the glass and forms a mirror. This reaction is used commercially to silver some mirrors (see **Figure 14.6**).

© Michael C. Slabaugh

FIGURE 14.6 This young woman can see herself because the silver coating on the back of the mirror reflects light.

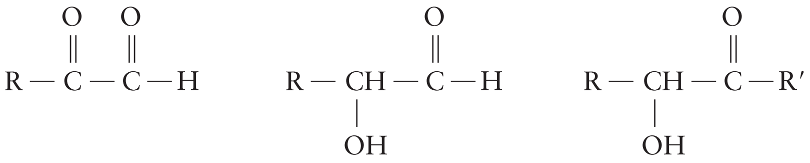
Benedict's reagent is a mild oxidizing solution containing Cu^{2+} ions. When an aldehyde oxidation takes place in an alkaline solution containing Cu^{2+}, a red precipitate of Cu_2O is produced:

Benedict's reagent A mild oxidizing solution containing Cu^{2+} ions used to test for the presence of aldehydes.



$$\underset{\text{certain aldehydes}}{R-\overset{\overset{\displaystyle O}{\|}}{C}-H} + \underset{\substack{\text{Benedict's}\\\text{reagent}\\\text{(blue)}}}{2Cu^{2+}} + 5OH^- \longrightarrow \underset{\text{carboxylate ion}}{R-\overset{\overset{\displaystyle O}{\|}}{C}-O^-} + \underset{\substack{\text{red}\\\text{precipitate}}}{Cu_2O} + 3H_2O \qquad (14.6)$$

The presence of Cu^{2+} in Benedict's reagent causes this alkaline solution to have a bright blue color. A positive Benedict's test consists of the appearance of a colored (usually red) precipitate. All aldehydes give a positive Tollens' test, but only certain aldehydes and one type of easily oxidized ketone readily give a positive Benedict's test. The necessary structural features are shown here:



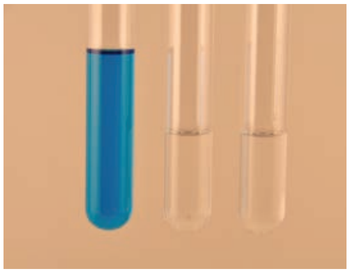
$$R-\overset{\overset{\displaystyle O}{\|}}{C}-\overset{\overset{\displaystyle O}{\|}}{C}-H \qquad R-\underset{\underset{\displaystyle OH}{|}}{CH}-\overset{\overset{\displaystyle O}{\|}}{C}-H \qquad R-\underset{\underset{\displaystyle OH}{|}}{CH}-\overset{\overset{\displaystyle O}{\|}}{C}-R'$$

a aldehyde with an adjacent carbonyl group

b aldehyde with an adjacent alcohol group

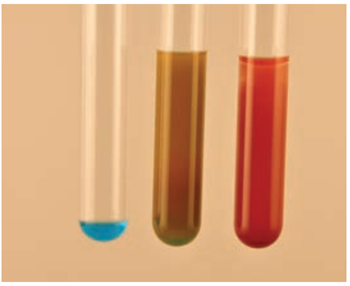
c ketone with an adjacent alcohol group

The structural features (parts b or c) are found in a number of sugars, including glucose. Accordingly, Benedict's reagent reacts with glucose to produce a red precipitate of Cu_2O (see **Figure 14.7**).



© Spencer L. Seager

1 From left to right, three test tubes containing Benedict's reagent, 0.5% glucose solution, and 2.0% glucose solution.



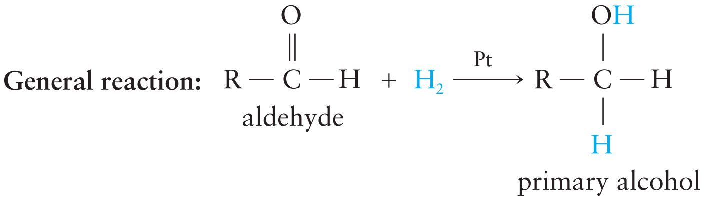
© Spencer L. Seager

2 The addition of Benedict's reagent from the first tube produces colors (due to the red Cu_2O) that indicate the amount of glucose present.

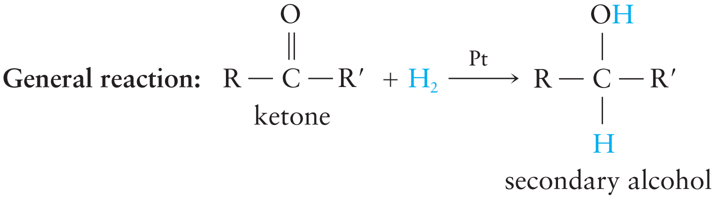
FIGURE 14.7 The Benedict's test for glucose.

14.3B The Addition of Hydrogen

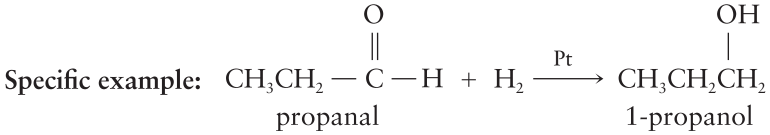
In **Section 12.3**, we learned that addition reactions are common for compounds containing carbon–carbon double bonds. The same is true for the carbon–oxygen double bonds of carbonyl groups. An important example is the addition of H_2 in the presence of catalysts such as nickel or platinum:



$$\textbf{General reaction: } \underset{\text{aldehyde}}{R-\overset{\overset{\displaystyle O}{\|}}{C}-H} + H_2 \xrightarrow{Pt} \underset{\text{primary alcohol}}{R-\underset{\underset{\displaystyle H}{|}}{\overset{\overset{\displaystyle OH}{|}}{C}}-H} \qquad (14.7)$$



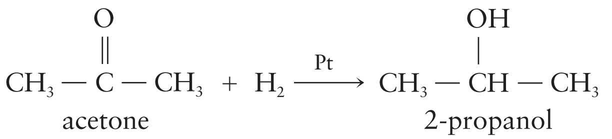
$$\textbf{General reaction: } \underset{\text{ketone}}{R-\overset{\overset{\displaystyle O}{\|}}{C}-R'} + H_2 \xrightarrow{Pt} \underset{\text{secondary alcohol}}{R-\underset{\underset{\displaystyle H}{|}}{\overset{\overset{\displaystyle OH}{|}}{C}}-R'} \qquad (14.8)$$



$$\textbf{Specific example: } \underset{\text{propanal}}{CH_3CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-H} + H_2 \xrightarrow{Pt} \underset{\text{1-propanol}}{CH_3CH_2\overset{\overset{\displaystyle OH}{|}}{CH_2}} \qquad (14.9)$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Specific example:

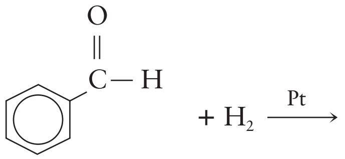


$$\underset{\text{acetone}}{CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-CH_3} + H_2 \xrightarrow{Pt} \underset{\text{2-propanol}}{CH_3-\overset{\overset{\displaystyle OH}{|}}{CH}-CH_3} \qquad (14.10)$$

We see that the addition of hydrogen to an aldehyde produces a primary alcohol, whereas the addition to a ketone gives a secondary alcohol. Notice that these reactions are reductions that are essentially the reverse of the alcohol oxidations used to prepare aldehydes and ketones (Reactions 14.1 and 14.2).

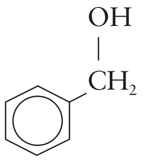
Example 14.4 Writing Hydrogenation Reactions

Benzaldehyde, the main flavor component in almonds, can react with hydrogen. Show the formula for the product of the following reaction.



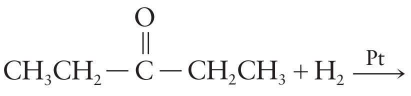
Solution

Hydrogen adds across the carbon–oxygen double bond, giving a primary alcohol as the product.



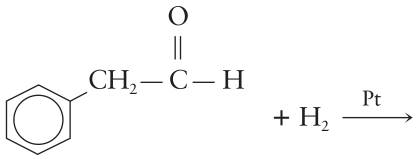
✔ **LEARNING CHECK 14.4** Draw the structural formula for each product of the following reactions:

a.



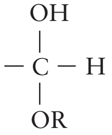
$$CH_3CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-CH_2CH_3 + H_2 \xrightarrow{Pt}$$

b.



hemiacetal

A compound that contains the functional group

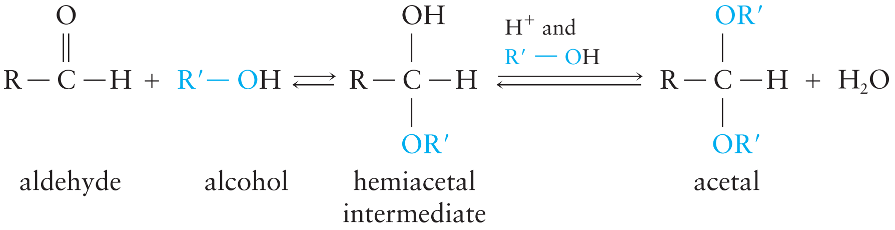


$$-\overset{\overset{\displaystyle OH}{|}}{\underset{\underset{\displaystyle OR}{|}}{C}}-H$$

14.3C The Addition of Alcohols

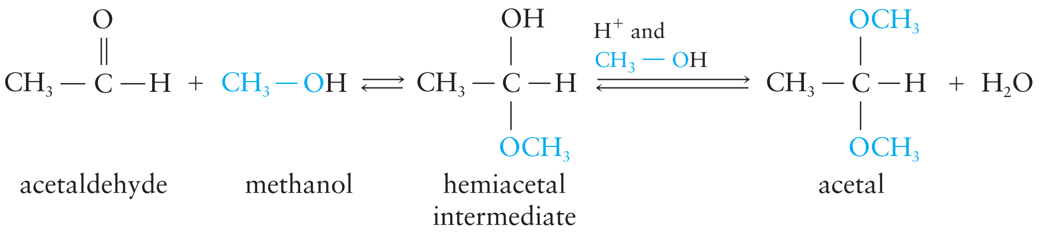
Aldehydes react with alcohols to form **hemiacetals**, a functional group that is very important in carbohydrate chemistry (**Chapter 17**). Hemiacetals are usually not very stable and are difficult to isolate. With excess alcohol present and with an acid catalyst, however, a stable product called an acetal is formed:

General reaction:



$$\underset{\text{aldehyde}}{R-\overset{\overset{\displaystyle O}{\|}}{C}-H} + \underset{\text{alcohol}}{R'-OH} \rightleftarrows \underset{\text{hemiacetal intermediate}}{R-\overset{\overset{\displaystyle OH}{|}}{\underset{\underset{\displaystyle OR'}{|}}{C}}-H} \xrightleftharpoons[R'-OH]{H^+\text{ and}} \underset{\text{acetal}}{R-\overset{\overset{\displaystyle OR'}{|}}{\underset{\underset{\displaystyle OR'}{|}}{C}}-H} + H_2O \qquad (14.11)$$

Specific example:



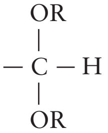
$$CH_3-\overset{\overset{O}{\|}}{C}-H + CH_3-OH \rightleftharpoons CH_3-\underset{\underset{OCH_3}{|}}{\overset{\overset{OH}{|}}{C}}-H \xrightleftharpoons{H^+\text{ and }CH_3-OH} CH_3-\underset{\underset{OCH_3}{|}}{\overset{\overset{OCH_3}{|}}{C}}-H + H_2O \qquad (14.12)$$

acetaldehyde
methanol
hemiacetal intermediate
acetal

Hemiacetals contain an —OH group, hydrogen, and an —OR group on the same carbon. Thus, a hemiacetal appears to have alcohol and ether functional groups. **Acetals** contain a carbon that has a hydrogen and two —OR groups attached; they look like diethers:

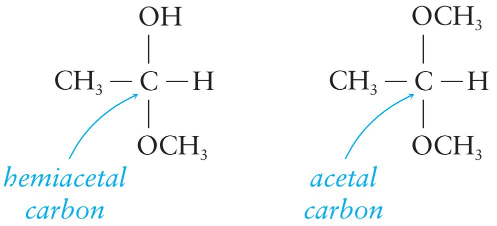
acetal

A compound that contains the



$$-\underset{\underset{OR}{|}}{\overset{\overset{OR}{|}}{C}}-H$$

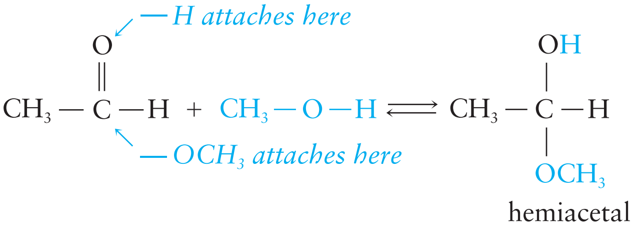
arrangement of atoms.



$$CH_3-\underset{\underset{OCH_3}{|}}{\overset{\overset{OH}{|}}{C}}-H \qquad CH_3-\underset{\underset{OCH_3}{|}}{\overset{\overset{OCH_3}{|}}{C}}-H$$

hemiacetal carbon
acetal carbon

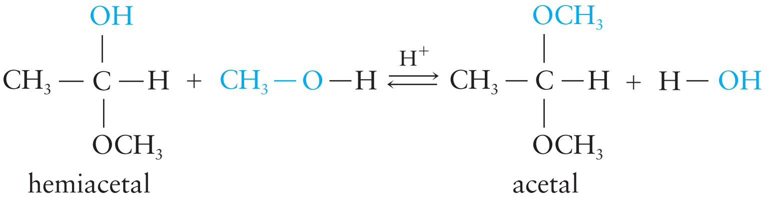
To better understand the changes that have occurred, let's look first at hemiacetal formation and then at acetal formation. The first molecule of alcohol adds across the double bond of the aldehyde in a manner similar to other addition reactions:



$$CH_3-\overset{\overset{O}{\|}}{C}-H + CH_3-O-H \rightleftharpoons CH_3-\underset{\underset{OCH_3}{|}}{\overset{\overset{OH}{|}}{C}}-H \qquad (14.13)$$

H attaches here
OCH$_3$ attaches here
hemiacetal

The second step, in which the hemiacetal is converted to an acetal, is like earlier substitution reactions. In this case, an —OCH_3 substitutes for an —OH:



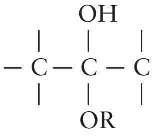
$$CH_3-\underset{\underset{OCH_3}{|}}{\overset{\overset{OH}{|}}{C}}-H + CH_3-O-H \overset{H^+}{\rightleftharpoons} CH_3-\underset{\underset{OCH_3}{|}}{\overset{\overset{OCH_3}{|}}{C}}-H + H-OH \qquad (14.14)$$

hemiacetal
acetal

In a very similar way, ketones can react with alcohols to form **hemiketals** and **ketals**:

hemiketal

A compound that contains the

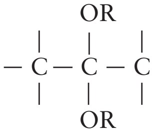


$$-\underset{|}{\overset{|}{C}}-\underset{\underset{OR}{|}}{\overset{\overset{OH}{|}}{C}}-\underset{|}{\overset{|}{C}}-$$

group.

ketal

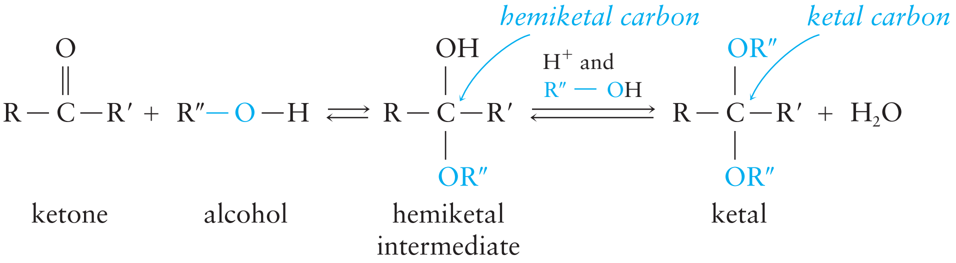
A compound that contains the



$$-\underset{|}{\overset{|}{C}}-\underset{\underset{OR}{|}}{\overset{\overset{OR}{|}}{C}}-\underset{|}{\overset{|}{C}}-$$

group.

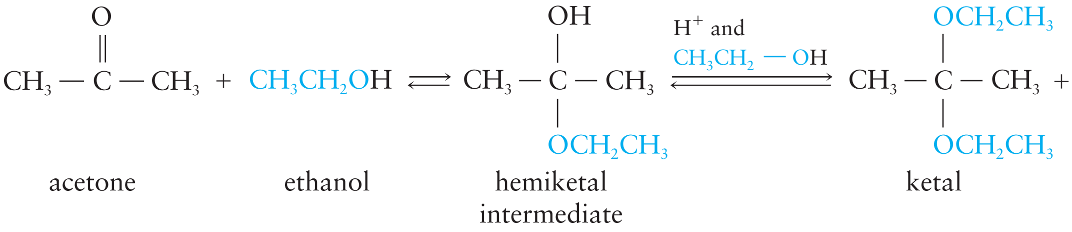
General reaction:



$$R-\overset{\overset{O}{\|}}{C}-R' + R''-O-H \rightleftharpoons R-\underset{\underset{OR''}{|}}{\overset{\overset{OH}{|}}{C}}-R' \xrightleftharpoons{H^+\text{ and }R''-OH} R-\underset{\underset{OR''}{|}}{\overset{\overset{OR''}{|}}{C}}-R' + H_2O \qquad (14.15)$$

hemiketal carbon
ketal carbon
ketone
alcohol
hemiketal intermediate
ketal

Specific example:



$$CH_3-\overset{\overset{O}{\|}}{C}-CH_3 + CH_3CH_2OH \rightleftharpoons CH_3-\underset{\underset{OCH_2CH_3}{|}}{\overset{\overset{OH}{|}}{C}}-CH_3 \xrightleftharpoons{H^+\text{ and }CH_3CH_2-OH} CH_3-\underset{\underset{OCH_2CH_3}{|}}{\overset{\overset{OCH_2CH_3}{|}}{C}}-CH_3 + H_2O \qquad (14.16)$$

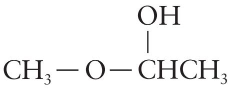
acetone
ethanol
hemiketal intermediate
ketal

Example 14.5 Identifying Functional Groups

Identify each of the following as a hemiacetal, a hemiketal, an acetal, a ketal, or none of these:

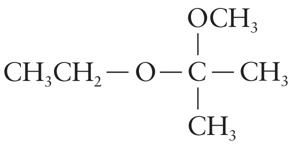
a. $CH_3—O—CH_2CH_2—OH$

b.



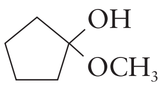
$$\mathrm{CH_3-O-\overset{\displaystyle OH}{\overset{|}{C}}HCH_3}$$

c.



$$\mathrm{CH_3CH_2-O-\overset{\displaystyle OCH_3}{\underset{\displaystyle CH_3}{\overset{|}{\underset{|}{C}}}}-CH_3}$$

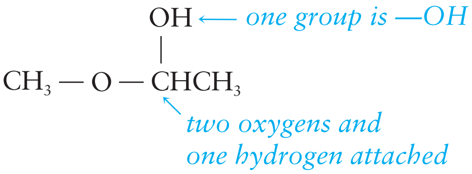
d.



Solution

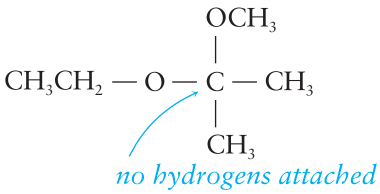
a. Look first at any structure to see if there is a carbon with two oxygens attached. Hemiacetals, hemiketals, acetals, and ketals are all alike in that regard. This compound has two oxygens, but they are on different carbons; thus it is none of the possibilities.

b. After finding a carbon with two oxygens attached, next look to see if one is an —OH. If it is, that makes it a hemiacetal or hemiketal. The third step is to look at the carbon containing the two oxygens. If it is attached to an —H, the compound was originally an aldehyde and not a ketone. Thus, this compound is a hemiacetal:



$$\mathrm{CH_3-O-\overset{\displaystyle OH}{\overset{|}{C}}HCH_3}$$

c. There is a carbon with two oxygens attached and neither is an —OH. Thus, the compound is an acetal or ketal:



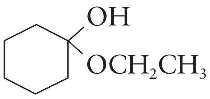
$$\mathrm{CH_3CH_2-O-\overset{\displaystyle OCH_3}{\underset{\displaystyle CH_3}{\overset{|}{\underset{|}{C}}}}-CH_3}$$

No hydrogens are attached to the carbon bonded to two oxygens. The compound is a ketal.

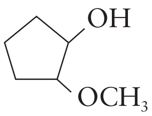
d. Two oxygens are attached to the same carbon. One group is an —OH. No hydrogens are attached to the central carbon. The compound is a hemiketal.

✔ **LEARNING CHECK 14.5** Identify each of the following as a hemiacetal, a hemiketal, an acetal, a ketal, or none of these:

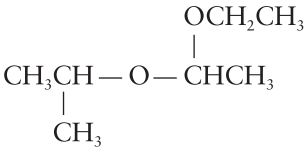
a.



b.

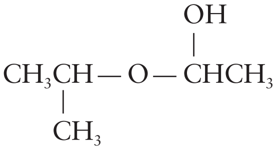


c.



$$\mathrm{CH_3\underset{\displaystyle CH_3}{\underset{|}{C}}H-O-\overset{\displaystyle OCH_2CH_3}{\overset{|}{C}}HCH_3}$$

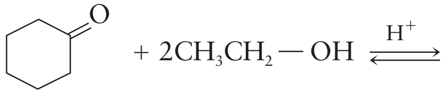
d.



$$\mathrm{CH_3\underset{\displaystyle CH_3}{\underset{|}{C}}H-O-\overset{\displaystyle OH}{\overset{|}{C}}HCH_3}$$

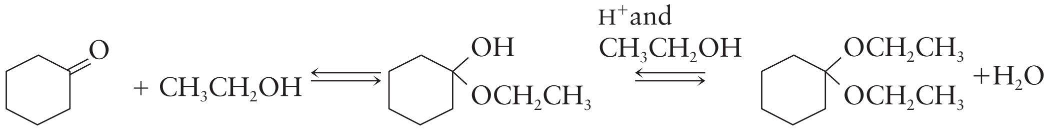
Example 14.6 More Writing Reaction Products

Cyclohexanone is used for the synthesis of nylon, pharmaceuticals, dyes, and many other products. Draw the structural formula for the hemiketal intermediate and for the ketal product of the following reaction:



Solution

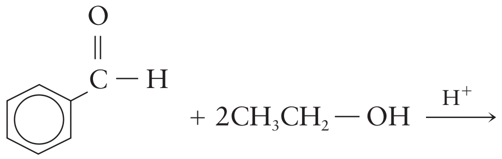
Using Key Reaction 14.15 as a guide, the reaction with one molecule of alcohol gives a hemiketal. Further reaction produces a ketal.



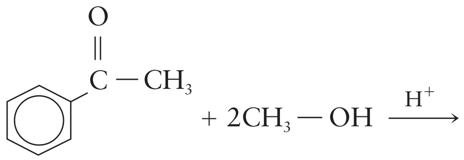
hemiketal ketal

✔ LEARNING CHECK 14.6 Draw the structural formula for the hemiacetal and hemiketal intermediates and for the acetal and ketal products of the following reactions. Label each structure as a hemiacetal, a hemiketal, a ketal, or an acetal.

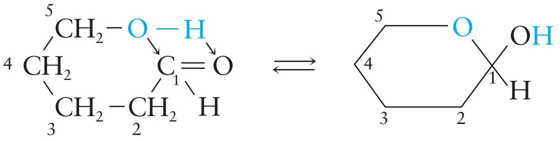
a.



b.



Some molecules contain both an —OH and a C═O group on different carbon atoms. In such cases, an intramolecular (within the molecule) reaction can occur, and a cyclic hemiacetal or hemiketal can be formed:



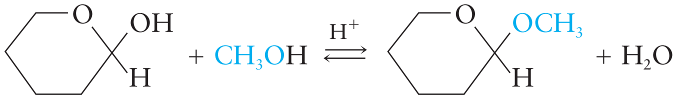
open-chain molecule containing an aldehyde and alcohol group

cyclic structure containing a hemiacetal group

(14.17)

Cyclic hemiacetals and hemiketals are much more stable than the open-chain compounds discussed earlier. In **Chapter 17**, we'll see that sugars such as glucose and fructose exist predominantly in the form of cyclic hemiacetals and hemiketals.

In another reaction important in carbohydrate chemistry (see **Chapter 17**), cyclic acetals and ketals may form from the hemistructures. As before, all reactions are reversible:



cyclic hemiacetal cyclic acetal

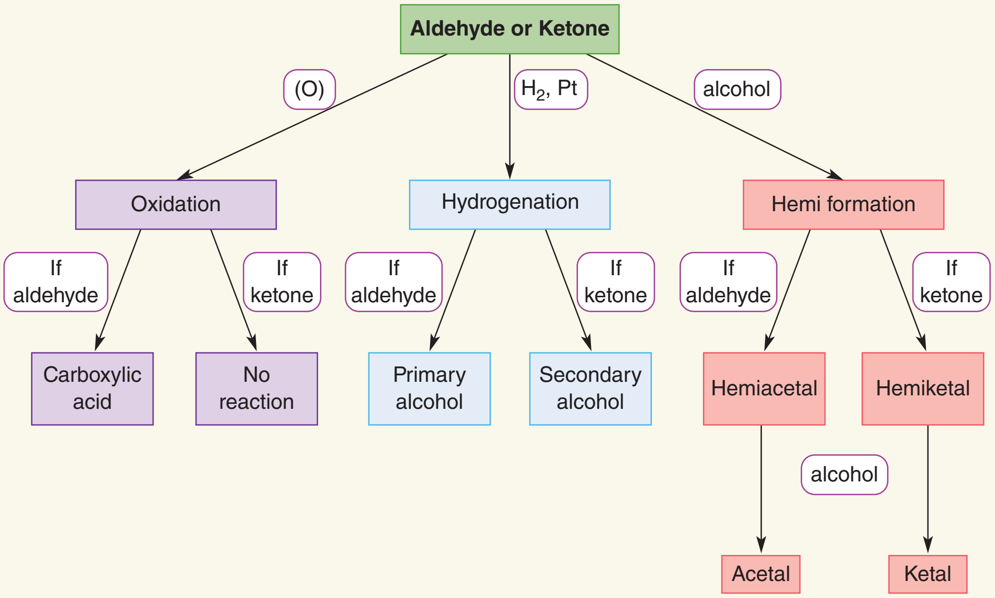
(14.18)

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STUDY TOOLS 14.1

A Reaction Map for Aldehydes and Ketones

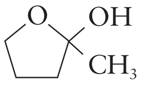
This reaction map is designed to help you master organic reactions. Whenever you are trying to complete an organic reaction, use these two basic steps: (1) Identify the functional group that is to react, and (2) Identify the reagent that is to react with the functional group. If the reacting functional group is an aldehyde or a ketone, find the reagent in the summary diagram, and use the diagram to predict the correct products.


Aldehyde or Ketone
(O)
H_2, Pt
alcohol
Oxidation
Hydrogenation
Hemi formation
If aldehyde
If ketone
If aldehyde
If ketone
If aldehyde
If ketone
Carboxylic acid
No reaction
Primary alcohol
Secondary alcohol
Hemiacetal
Hemiketal
alcohol
Acetal
Ketal

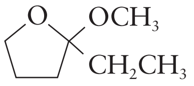
Example 14.7 More Identifying Functional Groups

Identify each of the following as a cyclic hemiacetal, a hemiketal, an acetal, or a ketal:

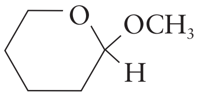
a.



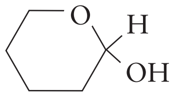
b.


O
OCH_3
CH_2CH_3

c.



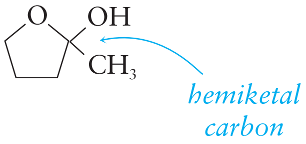
d.



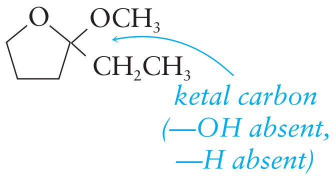
Solution

Use the same criteria that were applied to open-chain compounds in Example 14.3. Compound (A) has two oxygens attached to the same carbon. One is an —OH (hemiacetal or hemiketal). The central carbon has no hydrogens. Thus, the compound is a hemiketal. These criteria give the following results for each structure:

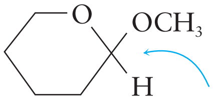
a.


O
OH
CH_3
hemiketal carbon

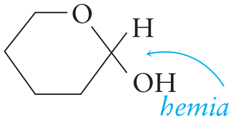
b.


O
OCH_3
CH_2CH_3
ketal carbon (—OH absent, —H absent)

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

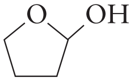
c. 

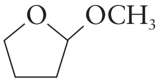
acetal carbon (—OH absent, —H present)

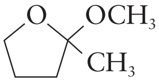
d. 

hemiacetal carbon (—OH present, —H present)

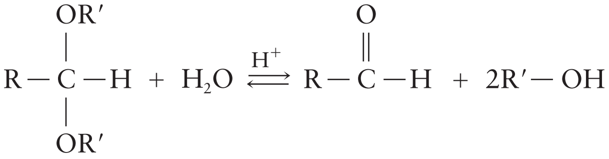
✔ LEARNING CHECK 14.7 Identify each of the following as a cyclic hemiacetal, a hemiketal, an acetal, or a ketal. Note that there may be hydrogen atoms not shown.

a. 

b. 

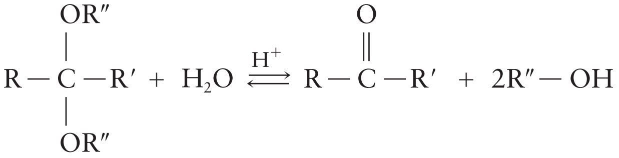
c. 

We have shown each of the reactions in acetal and ketal formation as being reversible. Simple hemiacetals and hemiketals are characteristically unstable and easily revert to the starting materials. Acetals and ketals are stable structures, but the reactions may be reversed by using water and an acid catalyst:

General reaction: 

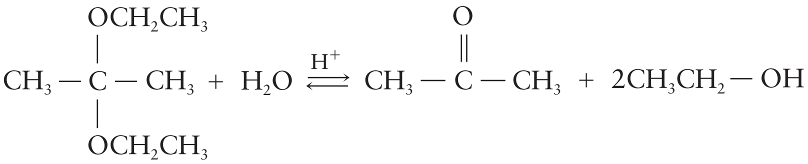
$$\mathrm{R-\underset{OR'}{\overset{OR'}{C}}-H + H_2O \overset{H^+}{\rightleftarrows} R-\overset{O}{\overset{\|}{C}}-H + 2R'-OH} \qquad (14.19)$$

acetal — aldehyde — alcohol

General reaction: 

$$\mathrm{R-\underset{OR''}{\overset{OR''}{C}}-R' + H_2O \overset{H^+}{\rightleftarrows} R-\overset{O}{\overset{\|}{C}}-R' + 2R''-OH} \qquad (14.20)$$

ketal — ketone — alcohol

Specific example: 

$$\mathrm{CH_3-\underset{OCH_2CH_3}{\overset{OCH_2CH_3}{C}}-CH_3 + H_2O \overset{H^+}{\rightleftarrows} CH_3-\overset{O}{\overset{\|}{C}}-CH_3 + 2CH_3CH_2-OH} \qquad (14.21)$$

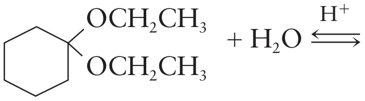
This type of reaction, in which water causes a compound to split into component substances, is called **hydrolysis**. It will be an important reaction to remember as we discuss, in later chapters, the chemistry of biomolecules such as carbohydrates, lipids, and proteins.

hydrolysis Bond breakage by reaction with water.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

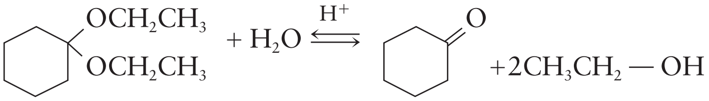
Example 14.8 Writing Hydrolysis Reactions

Draw the structural formulas needed to complete the following hydrolysis reaction:

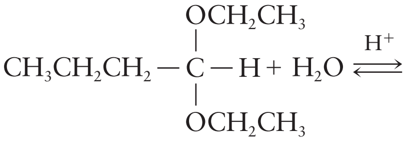


Solution

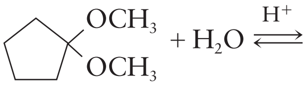
Using Key Reaction 14.20 as a guide, the products will be a ketone and two molecules of alcohol:



✔ LEARNING CHECK 14.8 Draw the structural formulas needed to complete the following hydrolysis reactions:

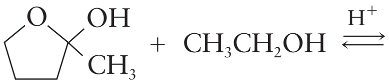
a. 

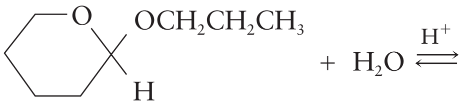
$$CH_3CH_2CH_2-\underset{\underset{OCH_2CH_3}{|}}{\overset{\overset{OCH_2CH_3}{|}}{C}}-H + H_2O \xrightleftharpoons{H^+}$$

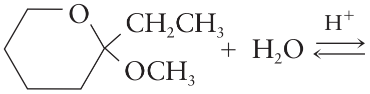
b. 

Example 14.9 Writing Reaction Products

Draw structural formulas for the products of the following reactions:

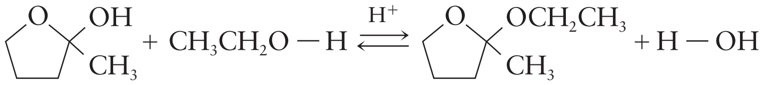
a. 

b. 

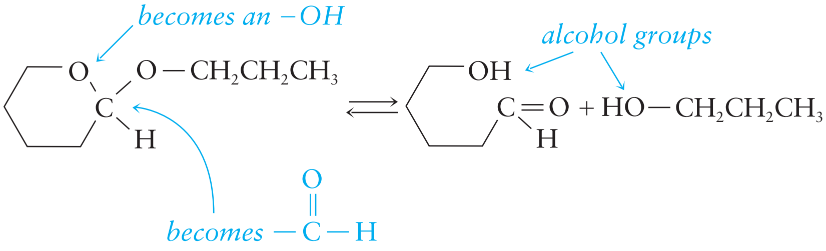
c. 

Solution

a. The starting material is a cyclic hemiketal. Reaction with an alcohol produces a cyclic ketal by a substitution of —OCH_2CH_3 for the —OH:



b. The starting compound is an acetal. Hydrolysis with water will form an aldehyde and two alcohol groups:



Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

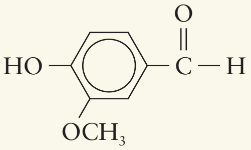
HEALTH CONNECTIONS 14.2

Vanilloids: Hot Relief from Pain

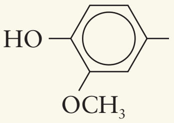
The word *vanilloids* might bring to mind images of vanilla-flavored candies or ice cream. However, vanilloids have properties very different from those of vanilla, and their inclusion in foods would result in a hot and spicy flavor that might even be extremely irritating, rather than a smooth vanilla flavor.

The best-known vanilloids are capsaicin and resiniferatoxin (RTX). Capsaicin is the compound in various types of hot peppers that gives them their characteristic hot and spicy flavor. It is used in a variety of products ranging from personal-defense pepper sprays to squirrel-proof birdseed. RTX is a powerful irritant extracted from a cactuslike plant, *Euphorbia resinifera.* The milky latex obtained from the plant is referred to in medical literature dating as far back as the first century. In these writings, it was described as a nose and skin irritant and as a treatment for chronic pain. In powdered form, RTX causes sneezing, a characteristic used by some practical jokers.

Structurally, molecules of capsaicin and RTX (not shown) are similar to those of vanillin in that they both have a homovanillyl group in their structure.

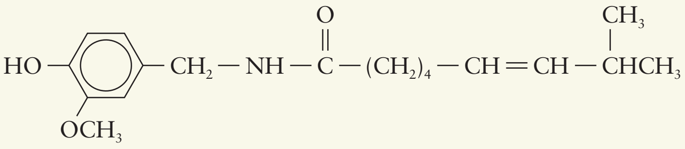


vanillin



homovanillyl group

When either of the compounds is applied to the skin or mouth, a burning sensation results. This sensation is caused by the compounds bonding to receptors of small sensory neurons associated with the transmission of pain. Following repeated application of capsaicin or RTX, these neurons, or C sensory nerve fibers, become desensitized to the initial irritation or pain the compounds cause. This characteristic allows the compounds to be used topically to relieve chronic pain. Capsaicin is now used as an ingredient in a few OTC pain-relieving creams such as Capzasin-P, Heet, Menthacin, and Pain Doctor.



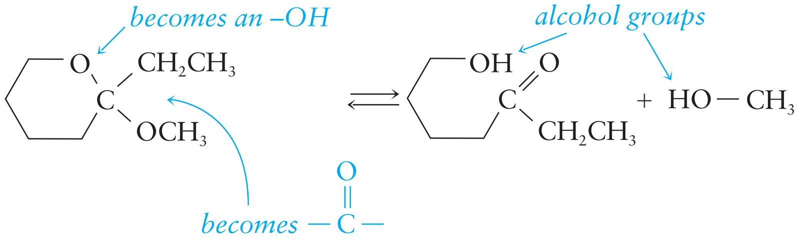
capsaicin

$6.99
$1.99
GREEN SERRANO PEPPERS
$1.99
PEPP

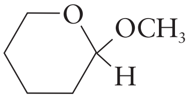
© Mark Slabaugh

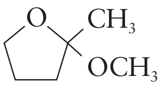
Hot peppers are a source of capsaicin.

c. The starting compound is a ketal. Hydrolysis with water will form a ketone and two alcohol groups:



✔ LEARNING CHECK 14.9 Identify each of the following as cyclic hemiacetals, hemiketals, acetals, or ketals and show structural formulas for the hydrolysis products:

a. 

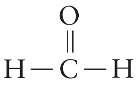
b. 

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

14.4 Important Aldehydes and Ketones

Learning Objective 5 Give specific uses for aldehydes and ketones.

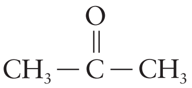
14.4A Formaldehyde:



$$H-\overset{\overset{O}{\|}}{C}-H$$

As seen with other functional classes, the most important compound of the class is usually the simplest member. Formaldehyde, the simplest aldehyde, is a gas at room temperature, but it is often supplied and used in the form of a 37% aqueous solution called *formalin*. This solution kills microorganisms and is effective in sterilizing surgical instruments. It is also used to embalm cadavers. Formaldehyde is a key industrial chemical in the production of plastics such as Bakelite®, the first commercial polymer invented in 1901, and Formica®.

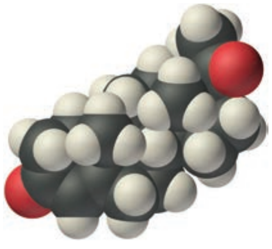
14.4B Acetone:



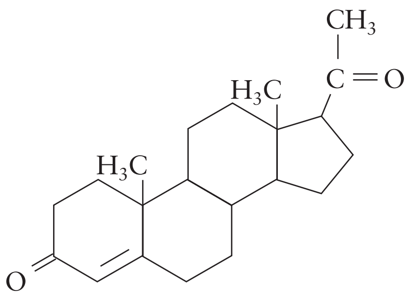
$$CH_3-\overset{\overset{O}{\|}}{C}-CH_3$$

Judging from the quantity used, acetone is by far the most important of the ketones. Over 1 billion pounds are used annually in the United States. It is particularly useful as a solvent because it dissolves most organic compounds and yet it is miscible in water. It is widely used as a solvent for coatings, which range from nail polish to exterior enamel paints (see **Figure 14.8**).

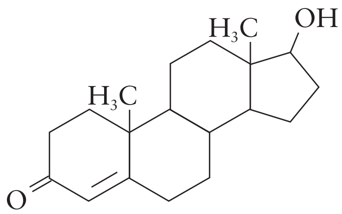
A number of naturally occurring aldehydes and ketones play important roles within living systems. The carbonyl functional group is fairly common in biological compounds. For example, progesterone and testosterone, female and male sex hormones, respectively, are both ketones.



Progesterone



progesterone



testosterone

Several naturally occurring aldehydes and ketones have very fragrant odors and are used in flavorings (see **Figure 14.9** and **Table 14.3**).

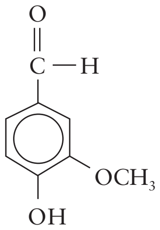
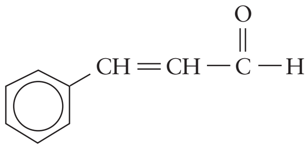
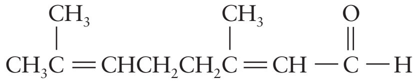
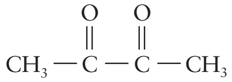
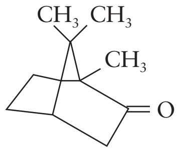
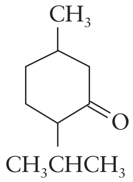
© Cengage Learning/Charles D. Winters

FIGURE 14.8 Acetone is an excellent solvent for many organics, including nail polish. Why does acetone-based polish remover evaporate fairly quickly when used?

RODNAE Productions/Pexels

FIGURE 14.9 Vanilla ice cream owes its characteristic flavor to a special aldehyde.

TABLE 14.3 Some Fragrant Aldehydes and Ketones

Name	Structural Formula	Sources and Typical Uses
Vanillin		Vanilla bean; flavoring
Cinnamaldehyde		Oil of cinnamon; flavoring
Citral	 $\overset{CH_3}{\overset{\vert}{CH_3C}}=CHCH_2CH_2\overset{CH_3}{\overset{\vert}{C}}=CH-\overset{O}{\overset{\Vert}{C}}-H$	Rinds of lemons, limes, and oranges; citrus flavoring
Biacetyl	 $CH_3-\overset{O}{\overset{\Vert}{C}}-\overset{O}{\overset{\Vert}{C}}-CH_3$	Butter; flavoring for margarines
Camphor		Camphor tree; characteristic medicinal odor; an ingredient in some inhalants
Menthone		Mint plants; peppermint flavoring

Health Career Description

NURSE PRACTITIONER

Nurse practitioners (NPs) must understand chemistry in order to understand physiology and medications. For instance, certain aldehydes perform essential functions in the human body, and there are a number of important ketone hormones such as progesterone, testosterone, cortisone, and aldosterone. Retinal is an aldehyde that combines with the protein (opsin) in the retina to form rhodopsin, the main compound involved in vision. Chemistry is foundational to understanding bodily functions.

NPs are registered nurses who have earned at least a master's degree and a certificate in an area of specialization. They are expected to continue their education throughout their career. They must participate in educational training to maintain their licenses. Some states require that NPs work under the authority of a physician.

The job duties of an NP include, but are not limited to, diagnosing acute illness, injury, or infection; prescribing medications, ordering diagnostic tests, teaching patients about health management and recording patient's medical histories and providing guidance to patients about medication interactions and side effects.

Many opportunities for NP specialties exist. Here are some of them:

- Family NP
- Pediatric NP
- Adult NP
- Geriatric NP
- Women's health NP
- Neonatal NP
- Occupational health NP
- Certified nurse midwife
- Certified registered NP
- Acute care NP
- Rural NP

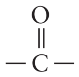
Communities depend on NPs to fill the need for patient care in the many areas where patients are better served by nursing practices than doctors.

Concept Summary

14.1 The Nomenclature of Aldehydes and Ketones

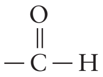
Learning Objective: Can you recognize the carbonyl group in compounds and classify the compounds as aldehydes or ketones? Can you assign IUPAC name to aldehydes and ketones?

- The functional groups characteristic of aldehydes and ketones are very similar.



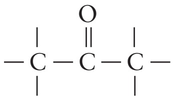
$$-\overset{O}{\overset{\|}{C}}-$$

- They both contain a carbonyl group.
- Aldehydes have a hydrogen attached to the carbonyl carbon.



$$-\overset{O}{\overset{\|}{C}}-H$$

- Ketones have two carbons attached to the carbonyl carbon.



$$-\underset{|}{\overset{|}{C}}-\overset{O}{\overset{\|}{C}}-\underset{|}{\overset{|}{C}}-$$

- The IUPAC ending for aldehyde names is *-al*, whereas the IUPAC ending for ketones is *-one*.

14.2 Physical Properties

Learning Objective: Can you compare the physical properties of aldehydes and ketones with those of compounds in other classes?

- Molecules of aldehydes and ketones cannot form hydrogen bonds with each other.
- As a result, they have lower boiling points than alcohols of similar mocleuldar weight.
- Aldehydes and ketones have higher boiling points than alkanes of similar molecular weight because of the presence of the polar carbonyl group.
- The polarity of the carbonyl group and the fact that aldehydes and ketones can form hydrogen bonds with water explain why the low-molecular-weight compounds of these organic classes are water-soluble.

14.3 Chemical Properties

Learning Objective: Can you write key reactions for aldehydes and ketones?

- Aldehydes are prepared by the oxidation of primary alcohols.
- Ketones are prepared by the oxidation of secondary alcohols.
- Aldehydes can be further oxidized to carboxylic acids, but ketones resist oxidation.
- Thus, aldehydes are oxidized by Tollens' reagent (Ag^+) and Benedict's solution (Cu^{2+}), whereas ketones are not.
- A characteristic reaction of both aldehydes and ketones is the addition of hydrogen to the carbonyl double bond to form alcohols.
- In a reaction that is very important in sugar chemistry, an alcohol can add across the carbonyl group of an aldehyde to produce a hemiacetal.
- The substitution reaction of a second alcohol molecule with the hemiacetal produces an acetal.
- Ketones can undergo similar reactions to form hemiketals and ketals.

14.4 Important Aldehydes and Ketones

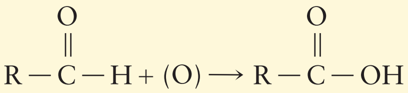
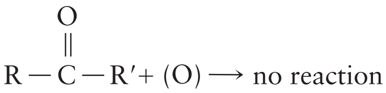
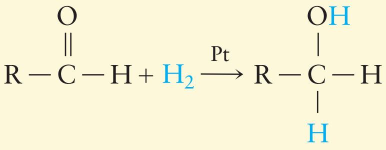
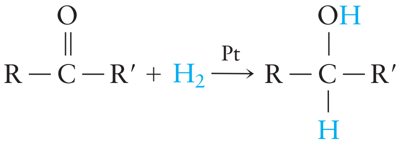
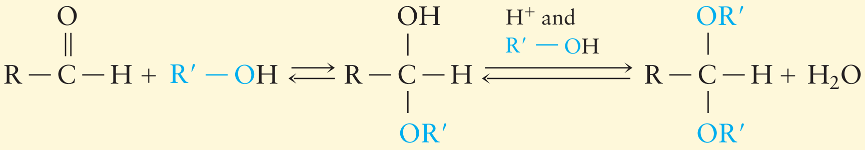
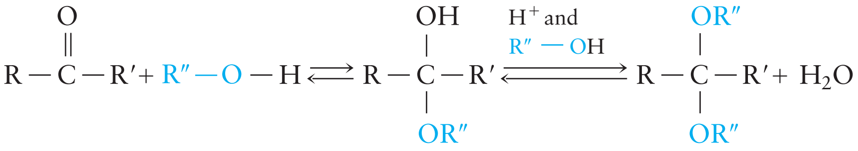
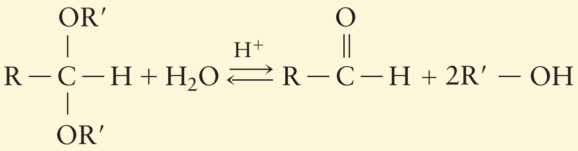
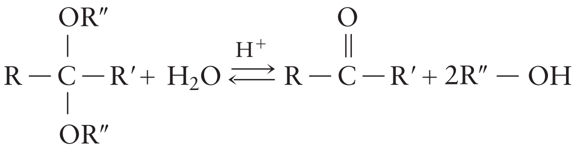
Learning Objective: Can you give specific uses for aldehydes and ketones?

- Formaldehyde is a key industrial chemical in the production of plastics such as Bakelite® and Formica®.
- Acetone is an important solvent.
- Some naturally occurring aldehydes and ketones are important in living systems.
- Some function as sex hormones; others are used as flavorings.

Key Terms and Concepts

Acetal (14.3)
Aldehyde (14.1)
Benedict's reagent (14.3)
Carbonyl group (Introduction)
Hemiacetal (14.3)
Hemiketal (14.3)
Hydrolysis (14.3)
Ketal (14.3)
Ketone (14.1)
Tollens' reagent (14.3)

Key Equations

1. Oxidation of an aldehyde to give a carboxylic acid (**Section 14.3**):	 $R-\overset{O}{\overset{\|}{C}}-H + (O) \longrightarrow R-\overset{O}{\overset{\|}{C}}-OH$	Reaction 14.1
2. Attempted oxidation of a ketone (**Section 14.3**):	 $R-\overset{O}{\overset{\|}{C}}-R' + (O) \longrightarrow \text{no reaction}$	Reaction 14.2
3. Hydrogenation of an aldehyde to give a primary alcohol (**Section 14.3**):	 $R-\overset{O}{\overset{\|}{C}}-H + H_2 \xrightarrow{Pt} R-\underset{H}{\underset{\mid}{\overset{OH}{\overset{\mid}{C}}}}-H$	Reaction 14.7
4. Hydrogenation of a ketone to give a secondary alcohol (**Section 14.3**):	 $R-\overset{O}{\overset{\|}{C}}-R' + H_2 \xrightarrow{Pt} R-\underset{H}{\underset{\mid}{\overset{OH}{\overset{\mid}{C}}}}-R'$	Reaction 14.8
5. Addition of an alcohol to an aldehyde to form a hemiacetal and then an acetal (**Section 14.3**):	 $R-\overset{O}{\overset{\|}{C}}-H + R'-OH \rightleftharpoons R-\underset{OR'}{\underset{\mid}{\overset{OH}{\overset{\mid}{C}}}}-H \xrightleftharpoons[R'-OH]{H^+\text{ and}} R-\underset{OR'}{\underset{\mid}{\overset{OR'}{\overset{\mid}{C}}}}-H + H_2O$	Reaction 14.11
6. Addition of an alcohol to a ketone to form a hemiketal and a ketal (**Section 14.3**):	 $R-\overset{O}{\overset{\|}{C}}-R' + R''-O-H \rightleftharpoons R-\underset{OR''}{\underset{\mid}{\overset{OH}{\overset{\mid}{C}}}}-R' \xrightleftharpoons[R''-OH]{H^+\text{ and}} R-\underset{OR''}{\underset{\mid}{\overset{OR''}{\overset{\mid}{C}}}}-R' + H_2O$	Reaction 14.15
7. Hydrolysis of an acetal to yield an aldehyde and two molecules of alcohol (**Section 14.3**):	 $R-\underset{OR'}{\underset{\mid}{\overset{OR'}{\overset{\mid}{C}}}}-H + H_2O \overset{H^+}{\rightleftharpoons} R-\overset{O}{\overset{\|}{C}}-H + 2R'-OH$	Reaction 14.19
8. Hydrolysis of a ketal to yield a ketone and two molecules of alcohol (**Section 14.3**):	 $R-\underset{OR''}{\underset{\mid}{\overset{OR''}{\overset{\mid}{C}}}}-R' + H_2O \overset{H^+}{\rightleftharpoons} R-\overset{O}{\overset{\|}{C}}-R' + 2R''-OH$	Reaction 14.20

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

The Nomenclature of Aldehydes and Ketones (Section 14.1)

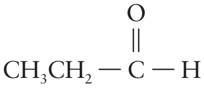
14.1 What is the structural difference between an aldehyde and a ketone?

14.2 Draw structural formulas for an aldehyde and a ketone that contain the fewest number of carbon atoms possible.

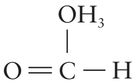
14.3 Oxybenzone is a useful component in sunscreens because of its UV light absorbing property. What does the ending of the common name oxybenzone imply about its structure?

14.4 Indicate which of the following compounds contains a carbonyl group:

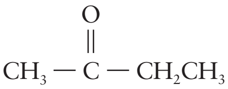
a. $CH_3{-}O{-}CH_2CH_3$

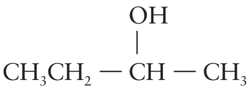
b. 
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-H$

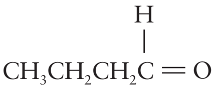
c. $CH_3CH_2{-}OH$

d. 
$O{=}\overset{OH_3}{\overset{|}{C}}-H$

14.5 Indicate which of the following compounds contains a carbonyl group:

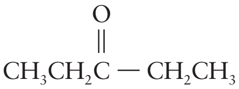
a. 
$CH_3-\overset{O}{\overset{\|}{C}}-CH_2CH_3$

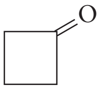
b. 
$CH_3CH_2-\overset{OH}{\overset{|}{CH}}-CH_3$

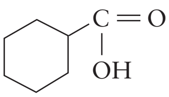
c. 
$CH_3CH_2CH_2\overset{H}{\overset{|}{C}}{=}O$

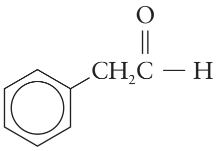
d. $CH_3{-}O{-}CH_3$

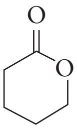
14.6 Identify each of the following compounds as an aldehyde, a ketone, or neither:

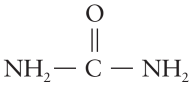
a. 
$CH_3CH_2\overset{O}{\overset{\|}{C}}-CH_2CH_3$

d. 

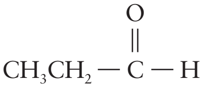
b. 

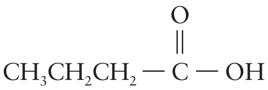
e. 

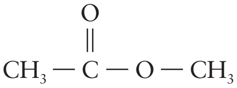
c. 

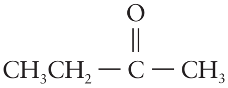
f. 
$NH_2-\overset{O}{\overset{\|}{C}}-NH_2$

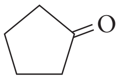
14.7 Identify each of the following compounds as an aldehyde, a ketone, or neither:

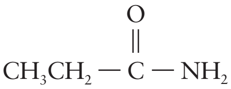
a. 
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-H$

d. 
$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-OH$

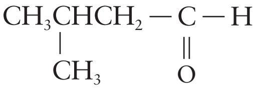
b. 
$CH_3-\overset{O}{\overset{\|}{C}}-O-CH_3$

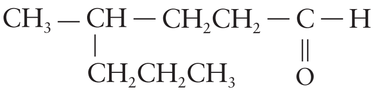
e. 
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-CH_3$

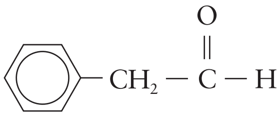
c. 

f. 
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-NH_2$

14.8 Assign IUPAC names to the following aldehydes:

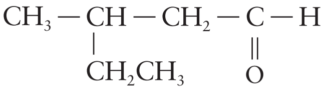
a. 
$\underset{\underset{CH_3}{|}}{CH_3CH}CH_2-\underset{\underset{O}{\|}}{C}-H$

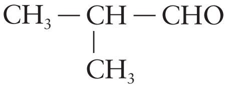
b. 
$CH_3-\underset{\underset{CH_2CH_2CH_3}{|}}{CH}-CH_2CH_2-\underset{\underset{O}{\|}}{C}-H$

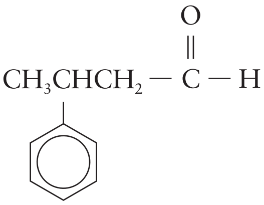
c. 

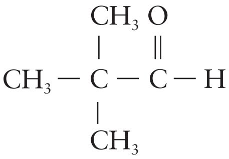
d. $CH_3CH_2CH_2CHO$

14.9 Assign IUPAC names to the following aldehydes:

a. 
$CH_3-\underset{\underset{CH_2CH_3}{|}}{CH}-CH_2-\underset{\underset{O}{\|}}{C}-H$

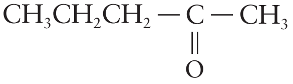
b. 
$CH_3-\underset{\underset{CH_3}{|}}{CH}-CHO$

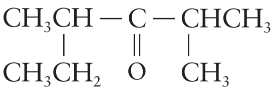
c. 

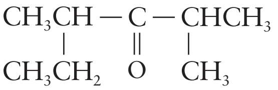
d. 
$CH_3-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}}-\overset{O}{\overset{\|}{C}}-H$

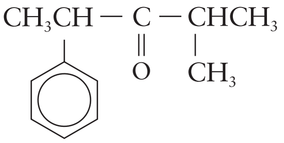
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

14.10 Assign IUPAC names to the following ketones:

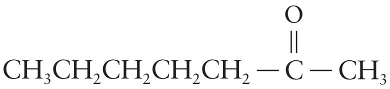
a. 
$CH_3CH_2CH_2-\underset{\underset{\displaystyle O}{\|}}{C}-CH_3$

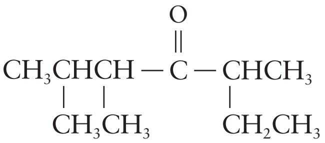
b. 
$\underset{\underset{\displaystyle CH_3CH_2}{|}}{CH_3CH}-\underset{\underset{\displaystyle O}{\|}}{C}-\underset{\underset{\displaystyle CH_3}{|}}{CHCH_3}$

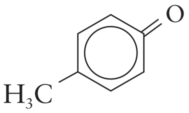
c. 
$\underset{\underset{\displaystyle CH_3CH_2}{|}}{CH_3CH}-\underset{\underset{\displaystyle O}{\|}}{C}-\underset{\underset{\displaystyle CH_3}{|}}{CHCH_3}$

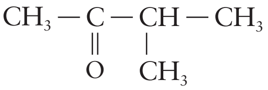
d. 

14.11 Assign IUPAC names to the following ketones:

a. 
$CH_3CH_2CH_2CH_2CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-CH_3$

b. 
$CH_3\underset{\underset{\displaystyle CH_3}{|}}{CH}\underset{\underset{\displaystyle CH_3}{|}}{CH}-\overset{\overset{\displaystyle O}{\|}}{C}-\underset{\underset{\displaystyle CH_2CH_3}{|}}{CH}CH_3$

c. 

d. 
$CH_3-\underset{\underset{\displaystyle O}{\|}}{C}-\underset{\underset{\displaystyle CH_3}{|}}{CH}-CH_3$

14.12 Draw structural formulas for the following aldehydes:

a. 3-methylhexanal

b. 2,3-dibromobutanal

c. 3,3-dimethylpentanal

d. 3-phenylpropanal

14.13 Draw structural formulas for the following aldehydes:

a. 2,4,5-trimethyloctanal

b. 2-hydroxy-3-methylhexanal

c. 4,4-dimethyl-3-phenylpentanal

d. Butanal

14.14 Draw structural formulas for the following ketones:

a. Cyclopentanone

b. 2-hexanone

c. 1,2-dichloro-3-pentanone

d. 3-phenyl-2-pentanone

14.15 Draw structural formulas for the following ketones:

a. 1,5-dibromo-2-pentanone

b. 3-methylcyclohexanone

c. 1,3,4-trichloro-2-butanone

d. 4-hydroxy-5-phenyl-2-hetpanone

14.16 Provide correct IUPAC names for all the ketone isomers that have the name 2-ethyl-*x*-hexanone, where *x* is any integer.

14.17 Provide correct IUPAC names for all the ketone isomers that have the name *x*-methyl-2-pentanone, where *x* is any integer.

14.18 Draw structural formulas and give IUPAC names for all the isomeric aldehydes and ketones that have the molecular formula $C_5H_{10}O$.

14.19 Draw structural formulas and give IUPAC names for all the isomeric aldehydes and ketones that have the molecular formula C_3H_6O.

14.20 Each of the following names is wrong. Give the structure and correct name for each compound.

a. 3-ethyl-2-butanone

b. 2-ethyl-propanal

c. 4-methyl-5-propyl-3-hexanone

d. 2-methyl-2-phenylethanal

14.21 Each of the following names is wrong. Give the structure and correct name for each compound.

a. 3-ethyl-2-methylbutanal

b. 2-methyl-4-butanone

c. 4,5-dibromocyclopentanone

Physical Properties (Section 14.2)

14.22 Why does hydrogen bonding *not* take place between molecules of aldehydes or ketones?

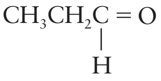
14.23 Most of the remaining water in washed laboratory glassware can be removed by rinsing the glassware with acetone (propanone). Explain how this process works (acetone is much more volatile than water).

14.24 The boiling point of propanal is 49°C, whereas the boiling point of propanol is 97°C. Explain this difference in boiling points.

14.25 Explain why propane boils at −42°C, whereas ethanal, which has the same molecular weight, boils at 20°C.

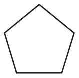
14.26 Arrange the following compounds in order of increasing water solubility:

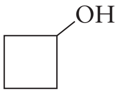
a. $CH_3CH_2CH_2{-}OH$

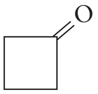
b. 
$CH_3CH_2\underset{\underset{\displaystyle H}{|}}{C}=O$

c. $CH_3CH_2CH_2CH_3$

14.27 Arrange the following compounds in order of increasing water solubility:

a. 

b. 

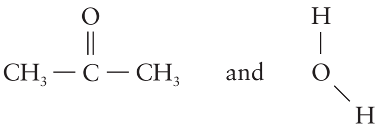
c. 

14.28 Explain why you would expect hexanal or ethanal to be more soluble in water.

14.29 Explain why you would expect 1-propanol or 1-propanone to be more soluble in water. Both have the same molecular weight.

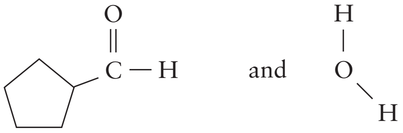
14.30 Use a dotted line to show hydrogen bonding between molecules in each of the following pairs:

a.



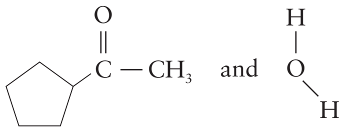
$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-CH_3$ and $\overset{\overset{\displaystyle H}{|}}{O}\diagdown H$

b.

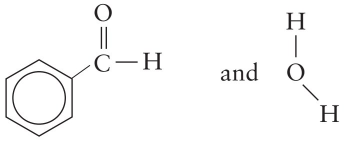


14.31 Use a dotted line to show hydrogen bonding between molecules in each of the following pairs:

a.



b.

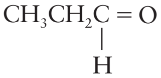


14.32 Arrange the following compounds in order of increasing boiling point:

a. $CH_3CH_2CH_2–OH$

b. $CH_3CH_2CH_2CH_3$

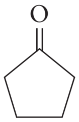
c.



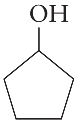
$CH_3CH_2\underset{\underset{\displaystyle H}{|}}{C}=O$

14.33 Arrange the following compounds in order of increasing boiling point:

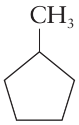
a.



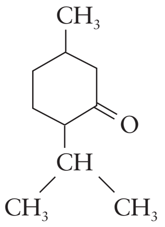
b.



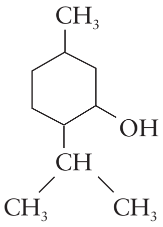
c.



14.34 The compounds menthone and menthol are fragrant substances present in an oil produced by mint plants:



menthone



menthol

When pure, one of these pleasant-smelling compounds is a liquid at room temperature; the other is a solid. Identify the solid and the liquid and explain your reasoning.

14.35 Draw the structural formula of the alcohol needed to make each of the following aldehydes or ketones:

a. 3-ethylhexanal

b. cyclopentanone

c. 3-phenylpropanone

d. ethanal

14.36 Draw the structural formula of the alcohol needed to make each of the following aldehydes or ketones:

a. 3-hexanone

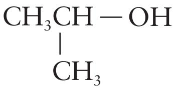
b. 2,3-dimethylhexanal

c. 2-methylcyclopentanone

d. Butanal

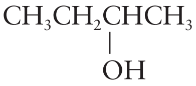
14.37 Draw the structure of the aldehyde or ketone formed from each of the following alcohols. Assume mild oxidizing conditions and no carboxylic acids are formed from any aldehydes produced.

a.



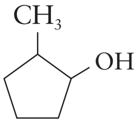
$CH_3\underset{\underset{\displaystyle CH_3}{|}}{CH}-OH$

b.

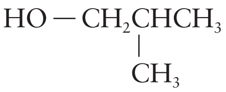


$CH_3CH_2\underset{\underset{\displaystyle OH}{|}}{CH}CH_3$

c.



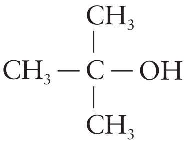
d.



$HO-CH_2\underset{\underset{\displaystyle CH_3}{|}}{CH}CH_3$

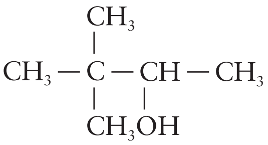
14.38 Draw the structure of the aldehyde or ketone formed from each of the following alcohols. Assume mild oxidizing conditions and no carboxylic acids are formed from any aldehydes produced.

a.



$CH_3-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-OH$

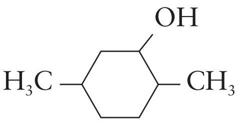
b.



$CH_3-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-\underset{\underset{\displaystyle OH}{|}}{CH}-CH_3$

c. $HO\text{-}CH_2CH_2CH_3$

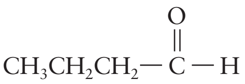
d.

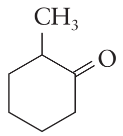


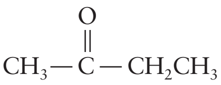
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Chemical Properties (Section 14.3)

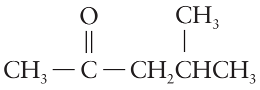
14.39 Write an equation for the formation of the following compounds from the appropriate alcohol:

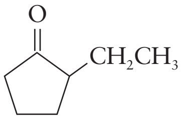
a. 
$CH_3CH_2CH_2-\overset{\substack{O\\\|}}{C}-H$

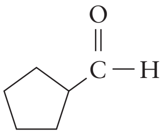
b. 

c. 
$CH_3-\overset{\substack{O\\\|}}{C}-CH_2CH_3$

14.40 Write an equation for the formation of the following compounds from the appropriate alcohol:

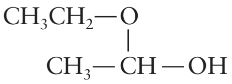
a. 
$CH_3-\overset{\substack{O\\\|}}{C}-CH_2\overset{\substack{CH_3\\|}}{C}HCH_3$

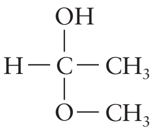
c. 

b. 

14.41 Identify which of the following structures are hemiacetals:

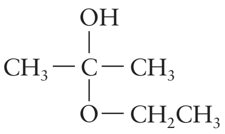
a. $CH_3CH_2-O-CH_2CH_3$

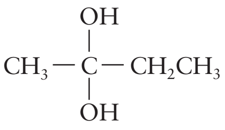
b. 
$CH_3-\overset{\substack{CH_3CH_2-O\\|}}{C}H-OH$

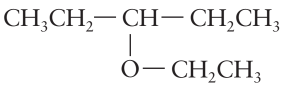
c. 
$H-\overset{\substack{OH\\|}}{\underset{\substack{|\\O-CH_3}}{C}}-CH_3$

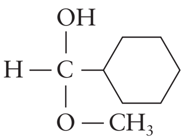
d. $HO-CH_2CH_2-O-CH_2CH_3$

14.42 Identify which of the following structures are hemiacetals:

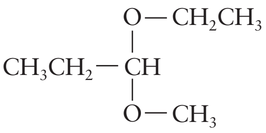
a. 
$CH_3-\overset{\substack{OH\\|}}{\underset{\substack{|\\O-CH_2CH_3}}{C}}-CH_3$

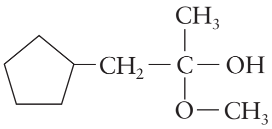
b. 
$CH_3-\overset{\substack{OH\\|}}{\underset{\substack{|\\OH}}{C}}-CH_2CH_3$

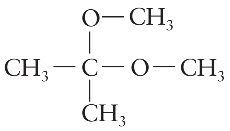
c. 
$CH_3CH_2-\underset{\substack{|\\O-CH_2CH_3}}{CH}-CH_2CH_3$

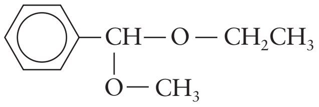
d. 

14.43 Identify which of the following structures are acetals:

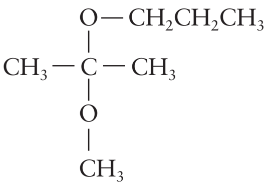
a. 
$CH_3CH_2-\overset{\substack{O-CH_2CH_3\\|}}{\underset{\substack{|\\O-CH_3}}{CH}}$

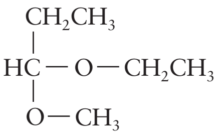
b. 

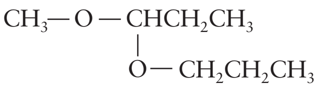
c. 
$CH_3-\overset{\substack{O-CH_3\\|}}{\underset{\substack{|\\CH_3}}{C}}-O-CH_3$

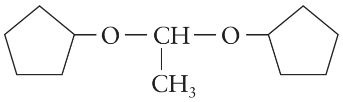
d. 

14.44 Identify which of the following structures are acetals:

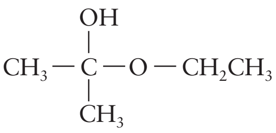
a. 
$CH_3-\overset{\substack{O-CH_2CH_2CH_3\\|}}{\underset{\substack{|\\O\\|\\CH_3}}{C}}-CH_3$

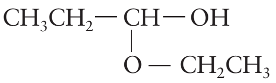
b. 
$\overset{\substack{CH_2CH_3\\|}}{\underset{\substack{|\\O-CH_3}}{HC}}-O-CH_2CH_3$

c. 
$CH_3-O-\underset{\substack{|\\O-CH_2CH_2CH_3}}{CH}CH_2CH_3$

d. 

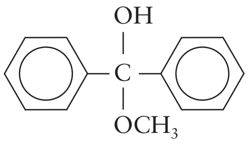
14.45 Identify which of the following structures are hemiketals:

a. 
$CH_3-\overset{\substack{OH\\|}}{\underset{\substack{|\\CH_3}}{C}}-O-CH_2CH_3$

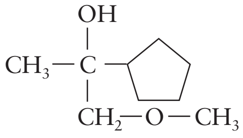
b. 
$CH_3CH_2-\underset{\substack{|\\O-CH_2CH_3}}{CH}-OH$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

c.

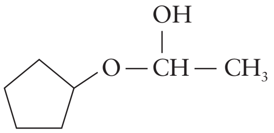


d.

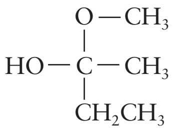


14.46 Identify which of the following structures are hemiketals:

a.

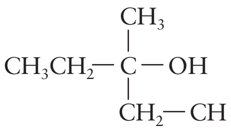


b.



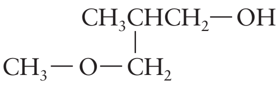
$$\mathrm{HO{-}\underset{CH_2CH_3}{\overset{O-CH_3}{C}}{-}CH_3}$$

c.



$$\mathrm{CH_3CH_2{-}\underset{CH_2-CH}{\overset{CH_3}{C}}{-}OH}$$

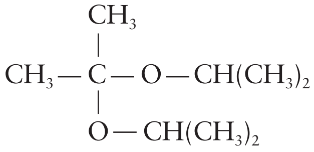
d.



$$\mathrm{CH_3{-}O{-}\overset{CH_3CHCH_2-OH}{CH_2}}$$

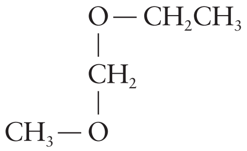
14.47 Identify which of the following structures are ketals:

a.



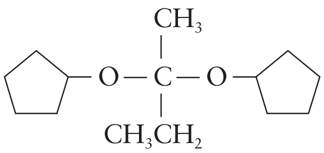
$$\mathrm{CH_3{-}\underset{O-CH(CH_3)_2}{\overset{CH_3}{C}}{-}O{-}CH(CH_3)_2}$$

b.

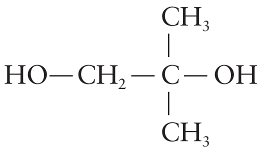


$$\begin{array}{l}\mathrm{O-CH_2CH_3}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{CH_3-O}\end{array}$$

c.



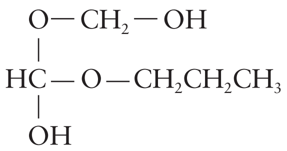
d.



$$\mathrm{HO{-}CH_2{-}\underset{CH_3}{\overset{CH_3}{C}}{-}OH}$$

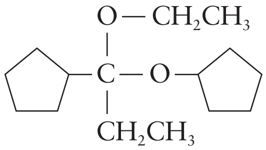
14.48 Identify which of the following structures are ketals:

a.

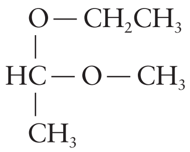


$$\mathrm{\underset{OH}{\overset{O-CH_2-OH}{HC}}{-}O{-}CH_2CH_2CH_3}$$

b.

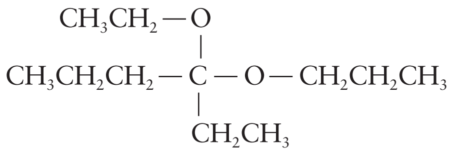


c.



$$\mathrm{\underset{CH_3}{\overset{O-CH_2CH_3}{HC}}{-}O{-}CH_3}$$

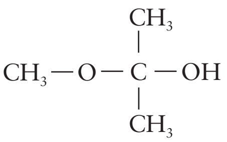
d.



$$\mathrm{CH_3CH_2CH_2{-}\underset{CH_2CH_3}{\overset{CH_3CH_2-O}{C}}{-}O{-}CH_2CH_2CH_3}$$

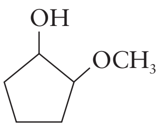
14.49 Identify the following structures as hemiacetals, hemiketals, or neither:

a.

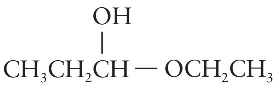


$$\mathrm{CH_3{-}O{-}\underset{CH_3}{\overset{CH_3}{C}}{-}OH}$$

c.

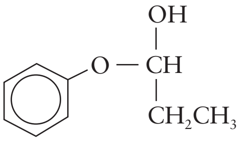


b.



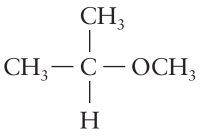
$$\mathrm{CH_3CH_2\overset{OH}{CH}{-}OCH_2CH_3}$$

d.



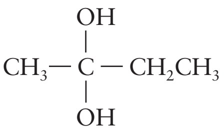
14.50 Identify the following structures as hemiacetals, hemiketals, or neither:

a.



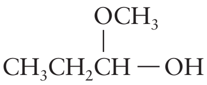
$$\mathrm{CH_3{-}\underset{H}{\overset{CH_3}{C}}{-}OCH_3}$$

c.



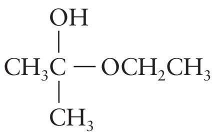
$$\mathrm{CH_3{-}\underset{OH}{\overset{OH}{C}}{-}CH_2CH_3}$$

b.



$$\mathrm{CH_3CH_2\overset{OCH_3}{CH}{-}OH}$$

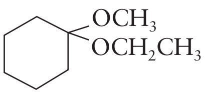
d.



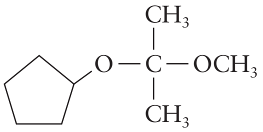
$$\mathrm{CH_3\underset{CH_3}{\overset{OH}{C}}{-}OCH_2CH_3}$$

14.51 Label each of the following as acetals, ketals, or neither:

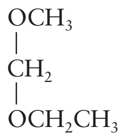
a.



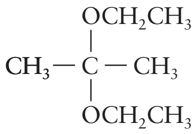
b.

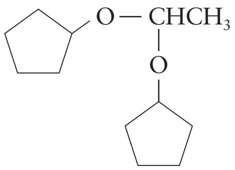


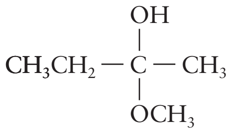
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

c. 
$$\begin{array}{c}\mathrm{OCH_3}\\ |\\ \mathrm{CH_2}\\ |\\ \mathrm{OCH_2CH_3}\end{array}$$

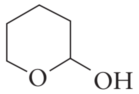
14.52 Label each of the following as acetals, ketals, or neither:

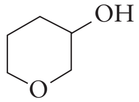
a. 
$$\mathrm{CH_3-\overset{\overset{\textstyle OCH_2CH_3}{|}}{\underset{\underset{\textstyle OCH_2CH_3}{|}}{C}}-CH_3}$$

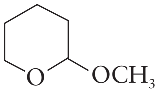
b. 

c. 
$$\mathrm{CH_3CH_2-\overset{\overset{\textstyle OH}{|}}{\underset{\underset{\textstyle OCH_3}{|}}{C}}-CH_3}$$

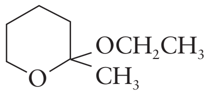
14.53 Label each of the following structures as a cyclic hemiacetal, a hemiketal, an acetal, a ketal, or none of these:

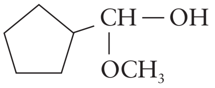
a. 

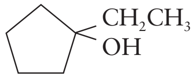
b. 

c. 

14.54 Label each of the following structures as a hemiacetal, a hemiketal, an acetal, a ketal, or none of these:

a. 

c. 

b. 

14.55 What two functional groups react to form the following?

a. A hemiacetal

b. An acetal

c. A ketal

d. A hemiketal

14.56 Hemiacetals are sometimes referred to as potential aldehydes. Explain.

14.57 Complete the following statements:

a. Oxidation of a secondary alcohol produces ________.

b. Oxidation of a primary alcohol produces an aldehyde that can be further oxidized to a ________.

c. Hydrogenation of a ketone produces ________.

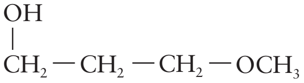
d. Hydrogenation of an aldehyde produces ________.

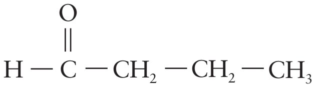
e. Hydrolysis of an acetal produces ________.

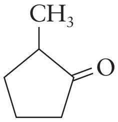
f. Hydrolysis of a ketal produces ________.

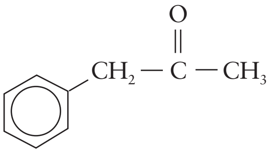
14.58 What observation characterizes a positive Tollens' test?

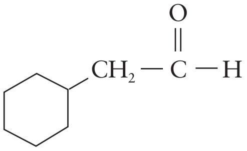
14.59 Which of the following compounds will react with Tollens' reagent (Ag^+, NH_3, and H_2O)? For those that do react, draw a structural formula for the organic product.

a. 
$$\mathrm{\overset{\overset{\textstyle OH}{|}}{C}H_2-CH_2-CH_2-OCH_3}$$

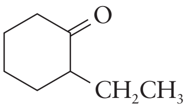
b. 
$$\mathrm{H-\overset{\overset{\textstyle O}{\|}}{C}-CH_2-CH_2-CH_3}$$

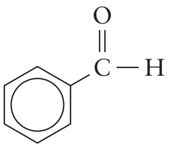
c. 

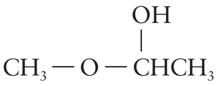
d. 

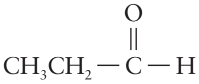
e. 

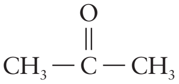
14.60 Which of the following compounds will react with Tollens' reagent (Ag^+, NH_3, and H_2O)? For those that do react, draw a structural formula for the organic product.

a. 

b. 

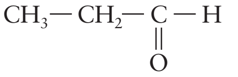
c. 
$$\mathrm{CH_3-O-\overset{\overset{\textstyle OH}{|}}{C}HCH_3}$$

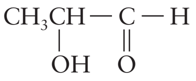
d. 
$$\mathrm{CH_3CH_2-\overset{\overset{\textstyle O}{\|}}{C}-H}$$

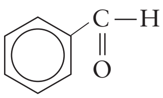
e. 
$$\mathrm{CH_3-\overset{\overset{\textstyle O}{\|}}{C}-CH_3}$$

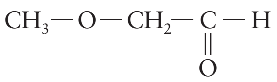
14.61 What is the formula of the precipitate that forms in a positive Benedict's test?

14.62 Not all aldehydes give a positive Benedict's test. Which of the following aldehydes do?

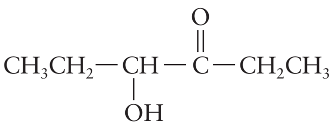
a. 
$$\mathrm{CH_3-CH_2-\underset{\underset{\textstyle O}{\|}}{C}-H}$$

b. 
$$\mathrm{CH_3\underset{\underset{\textstyle OH}{|}}{C}H-\underset{\underset{\textstyle O}{\|}}{C}-H}$$

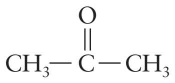
c. 

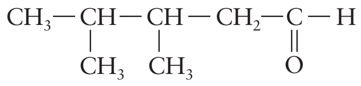
d. 
$$\mathrm{CH_3-O-CH_2-\underset{\underset{\textstyle O}{\|}}{C}-H}$$

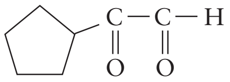
14.63 Not all aldehydes give a positive Benedict's test. Which of the following aldehydes do?

a. 
$$\mathrm{CH_3CH_2-\underset{\underset{\textstyle OH}{|}}{C}H-\overset{\overset{\textstyle O}{\|}}{C}-CH_2CH_3}$$

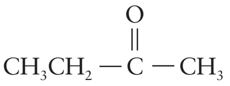
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

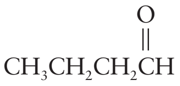
b. 
$CH_3-\overset{O}{\overset{\|}{C}}-CH_3$

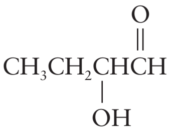
c. 
$CH_3-\underset{CH_3}{\underset{|}{CH}}-\underset{CH_3}{\underset{|}{CH}}-CH_2-\underset{O}{\underset{\|}{C}}-H$

d. 

14.64 A stockroom assistant prepares three bottles, each containing one of the following compounds:


$CH_3CH_2-\overset{O}{\overset{\|}{C}}-CH_3$

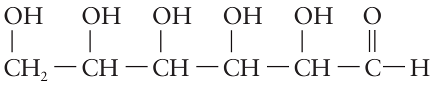

$CH_3CH_2CH_2\overset{O}{\overset{\|}{C}}H$


$CH_3CH_2\underset{OH}{\underset{|}{CH}}\overset{O}{\overset{\|}{C}}H$

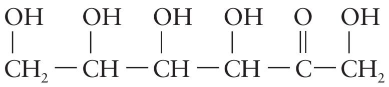
However, the bottles are left unlabeled. Instead of discarding the samples, another assistant runs tests on the contents, using Tollens' and Benedict's reagents. Match the compound to the bottle, based on these results.

	Tollens' Reagent	Benedict's Reagent
Bottle A	A dark precipitate forms	A red-orange precipitate forms
Bottle B	No reaction	No reaction
Bottle C	A dark precipitate and slight mirror form	No reaction

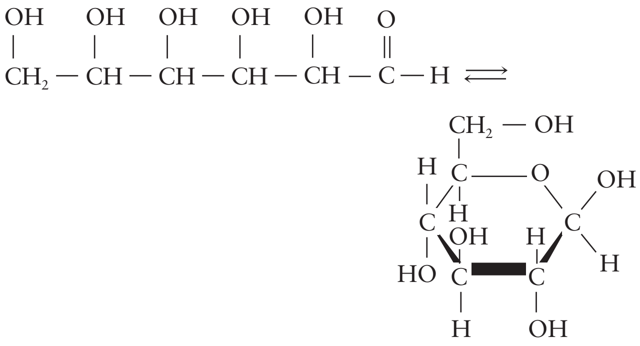
14.65 Glucose, the sugar present within the blood, gives a positive Benedict's test. Circle the structural features that enable glucose to react.


$\overset{OH}{\overset{|}{CH_2}}-\overset{OH}{\overset{|}{CH}}-\overset{OH}{\overset{|}{CH}}-\overset{OH}{\overset{|}{CH}}-\overset{OH}{\overset{|}{CH}}-\overset{O}{\overset{\|}{C}}-H$

14.66 Fructose, present with glucose in honey, reacts with Benedict's reagent. Circle the structural features that enable fructose to react.

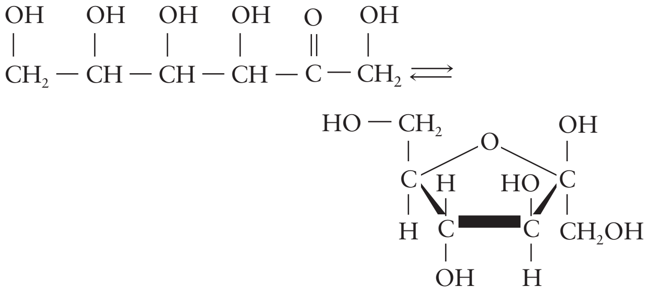

$\overset{OH}{\overset{|}{CH_2}}-\overset{OH}{\overset{|}{CH}}-\overset{OH}{\overset{|}{CH}}-\overset{OH}{\overset{|}{CH}}-\overset{O}{\overset{\|}{C}}-\overset{OH}{\overset{|}{CH_2}}$

14.67 Glucose can exist as a cyclic hemiacetal because one of the alcohol groups reacts with the aldehyde:



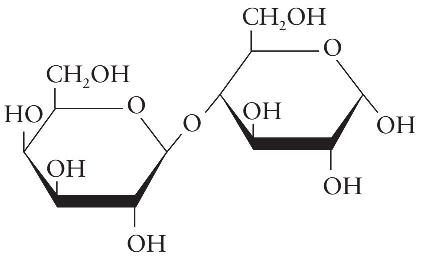
Draw an arrow to the carbon of the cyclic hemiacetal that was originally part of the aldehyde group. Circle the alcohol group in the open-chain structure that became a part of the cyclic hemiacetal.

14.68 After an intramolecular reaction, fructose forms a hemiketal:

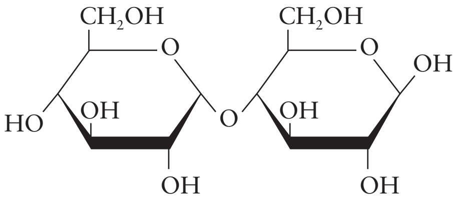


Draw an arrow to the carbon of the cyclic hemiketal that was originally part of the ketone group. Circle the alcohol group in the open-chain structure that became part of the cyclic hemiketal.

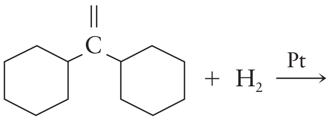
14.69 Lactose, or milk sugar, contains both an acetal group and a hemiacetal group. Circle both of these functional groups and identify them by name.

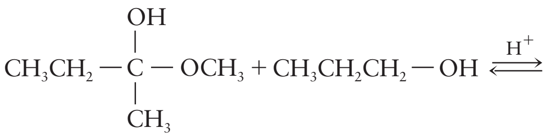


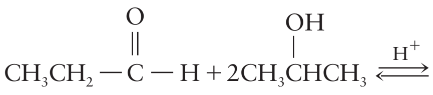
14.70 Maltose, produced by the hydrolysis of starches in grains, contains both an acetal and a hemiacetal group. Circle both of these functional groups and identify them by name.

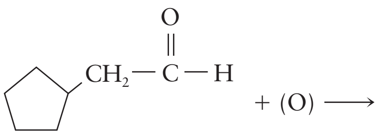


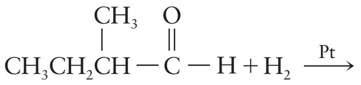
14.71 Complete the following equations. If no reaction occurs, write "no reaction."

a. 

b. 
$CH_3CH_2-\overset{OH}{\overset{|}{\underset{CH_3}{\underset{|}{C}}}}-OCH_3+CH_3CH_2CH_2-OH \xrightleftharpoons{H^+}$

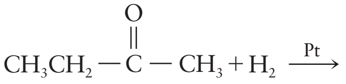
c. 
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-H+2CH_3\overset{OH}{\overset{|}{C}}HCH_3 \xrightleftharpoons{H^+}$

d. 

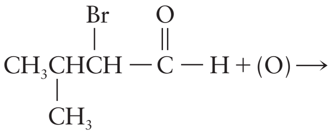
e. 
$CH_3CH_2\overset{CH_3}{\overset{|}{CH}}-\overset{O}{\overset{\|}{C}}-H+H_2 \xrightarrow{Pt}$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

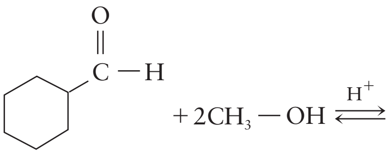
14.72 Complete the following equations. If no reaction occurs, write “no reaction.”

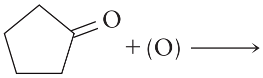
a. 

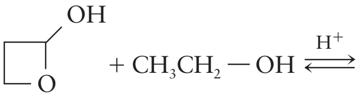
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-CH_3+H_2 \xrightarrow{Pt}$

b. 

$CH_3\underset{CH_3}{\underset{|}{CH}}\overset{Br}{\overset{|}{CH}}-\overset{O}{\overset{\|}{C}}-H+(O)\longrightarrow$

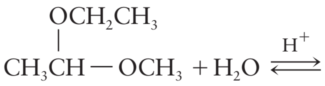
c. 

d. 

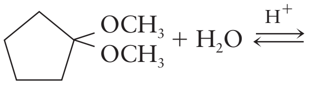
e. 

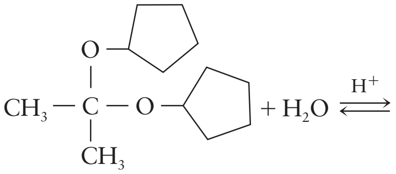
14.73 Describe the products that result when hydrogen (H_2) is added to alkenes, alkynes, aldehydes, and ketones. You might review Chapter 12 briefly.

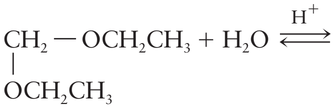
14.74 Draw structural formulas for the products of the following hydrolysis reactions:

a. 

$CH_3\overset{OCH_2CH_3}{\overset{|}{CH}}-OCH_3+H_2O \overset{H^+}{\rightleftarrows}$

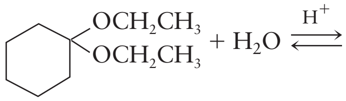
b. 

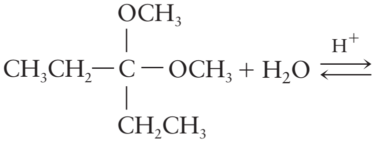
c. 

d. 

$\underset{OCH_2CH_3}{\underset{|}{CH_2}}-OCH_2CH_3+H_2O \overset{H^+}{\rightleftarrows}$

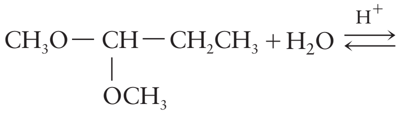
14.75 Draw structural formulas for the products of the following hydrolysis reactions:

a. 

b. 

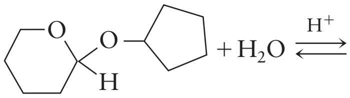
$CH_3CH_2-\overset{OCH_3}{\overset{|}{\underset{\underset{CH_2CH_3}{|}}{C}}}-OCH_3+H_2O \overset{H^+}{\rightleftarrows}$

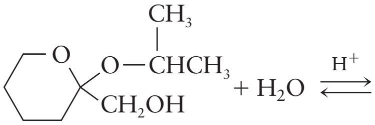
c. $CH_3CH_2CH_2O-CH_2-OCH_2CH_2CH_3+H_2O \overset{H^+}{\rightleftarrows}$

d. 

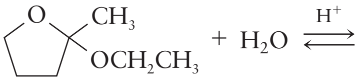
$CH_3O-\underset{OCH_3}{\underset{|}{CH}}-CH_2CH_3+H_2O \overset{H^+}{\rightleftarrows}$

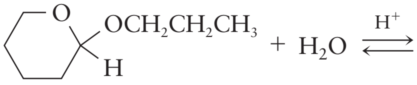
14.76 The following compounds are cyclic acetals or ketals. Write structural formulas for the hydrolysis products.

a. 

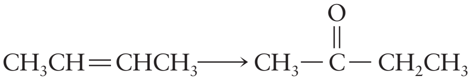
b. 

14.77 The following compounds are cyclic acetals or ketals. Write structural formulas for the hydrolysis products.

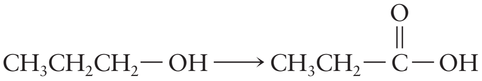
a. 

b. 

14.78* Write equations to show how the following conversions can be achieved. More than one reaction is required, and reactions from earlier chapters may be necessary.

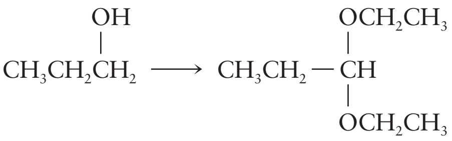
a. 

$CH_3CH{=}CHCH_3 \longrightarrow CH_3-\overset{O}{\overset{\|}{C}}-CH_2CH_3$

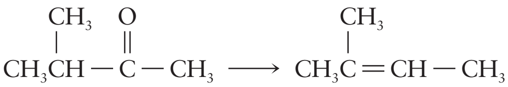
b. 

$CH_3CH_2CH_2-OH \longrightarrow CH_3CH_2-\overset{O}{\overset{\|}{C}}-OH$

14.79* Write equations to show how the following conversions can be achieved. More than one reaction is required, and reactions from earlier chapters may be necessary.

a. 

$CH_3CH_2\overset{OH}{\overset{|}{C}}H_2 \longrightarrow CH_3CH_2-\overset{OCH_2CH_3}{\overset{|}{\underset{\underset{OCH_2CH_3}{|}}{CH}}}$

b. 

$CH_3\overset{CH_3}{\overset{|}{C}}H-\overset{O}{\overset{\|}{C}}-CH_3 \longrightarrow CH_3\overset{CH_3}{\overset{|}{C}}{=}CH-CH_3$

Important Aldehydes and Ketones (Section 14.4)

14.80 Identify the most important aldehyde and ketone from **Section 14.4** (on the basis of amount used), and list at least one characteristic for each that contributes to its usefulness.

14.81 Using **Table 14.3**, name an aldehyde or ketone used in the following ways:

- **a.** Peppermint flavoring
- **b.** Flavoring for margarines
- **c.** Cinnamon flavoring
- **d.** Vanilla flavoring

14.82 Using **Table 14.3**, name an aldehyde or ketone used or found in the following ways:

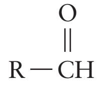
- **a.** Citrus flavoring
- **b.** Inhalant ingredient
- **c.** Found in mint plants
- **d.** Found in butter

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Additional Exercises

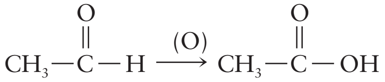
14.83 Arrange the following compounds starting with the carbon atom that is the most reduced and ending with the carbon that is the least reduced:

a. R—CH_2—OH

b. 

$R-\overset{\overset{\displaystyle O}{\|}}{C}H$

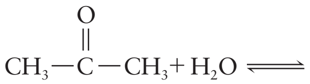
c. R—CH_3

14.84 

$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-H \xrightarrow{(O)} CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-OH$$

acetaldehyde acetic acid

You need to produce 500 g of acetic acid using the reaction above. The actual yield of the reaction is 79.6% of the theoretical yield. How many grams of acetaldehyde do you need to start with to produce 500 g of acetic acid?

14.85 

$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-CH_3 + H_2O \rightleftharpoons$$

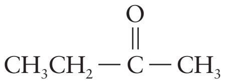
The addition of water to aldehydes and ketones occurs rapidly, although it is not thermodynamically favored. What would be the product for the reaction above? *Hint:* Think of the self-ionization of water and the polarity of the carbonyl group.

14.86 Draw the product that would result when 3-pentanone reacts with an excess of 1-propanol in the presence of an acid catalyst.

14.87 Formaldehyde levels above 0.10 mg/1000 L of ambient air can cause some humans to experience difficulty breathing. How many molecules of formaldehyde would be found in 1.0 L of air at this concentration?

Chemistry for Thought

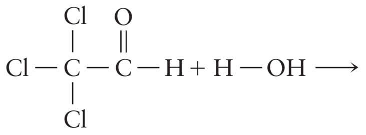
14.88 In the IUPAC name for the following ketone, it is not common to use a number for the position of the carbonyl group. Why not?



$$CH_3CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-CH_3$$

14.89 Why can formaldehyde (CH_2O) be prepared in the form of a 37% solution in water, whereas decanal ($C_{10}H_{20}O$) cannot?

14.90 Other addition reactions of aldehydes occur. Water, for example, adds to the carbonyl of trichloroacetaldehyde to form chloral hydrate, a strong hypnotic and sedative known as "knock-out drops" or (when mixed with alcohol) a "Mickey Finn." Complete the reaction by drawing the structural formula of chloral hydrate:

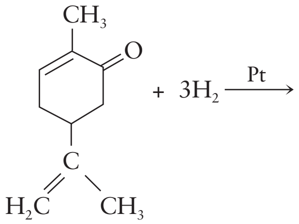


$$Cl-\underset{\underset{\displaystyle Cl}{|}}{\overset{\overset{\displaystyle Cl}{|}}{C}}-\overset{\overset{\displaystyle O}{\|}}{C}-H + H-OH \longrightarrow$$

trichloroacetaldehyde chloral hydrate

14.91 In the labels of some consumer products, ketone components listed with an *-one* ending can be found. However, very few aldehyde-containing (*-al* ending) products are found. How can you explain this?

14.92 Carvone, a component of spearmint oil, can consume 3 mol of hydrogen on hydrogenation in the presence of Pt. Show the product of this reaction.



14.93 In **Figure 14.8**, it is noted that acetone is used as a solvent in fingernail polish remover. Why do you think fingernail polish remover evaporates fairly quickly when used?

14.94 Vanilla flavoring is either extracted from a tropical orchid or synthetically produced from wood pulp by-products. What differences in chemical structure would you expect in these two commercial products: vanilla extract and imitation vanilla extract?

14.95 The structure of fructose in Exercise 14.66 reveals a ketone group and several alcohol groups. If the alcohol groups are referred to as hydroxys, give an IUPAC name for fructose.

14.96 The use of acetone in laboratory experiments must be carefully monitored because of the highly flammable nature of acetone. Give an equation for the combustion of acetone.

14.97 Look ahead to Chapter 17 and locate the structure of maltose in **Section 17.7**. Draw the structure of maltose and circle the acetal group.

15 Carboxylic Acids and Esters

Morsa Images/DigitalVision/Getty Images

Health Career Focus

PHARMACY TECHNICIAN

My parents believed in independence. I knew I couldn't live off mom and dad for college—I had to pay my own way—and I didn't want to borrow a lot of money. Luckily, my high school offered resources that helped position me for success—first, concurrent enrollment courses that gave high school and college credit simultaneously; second, free tech-school courses; and third, a great counselor.

My junior year in high school I took Chem 1110 and discovered that I love chemistry! Something "just clicked" with the way I visualize chemical reactions—I just "got it." My high school counselor suggested I try the pharmacy program at the technical college.

I was really interested in chemical flavorings (esters) and how to compound medications to make them more palatable and effective for certain individuals. I liked learning how to improve the flavor of children's medicine so that children would comply more easily with treatment.

By the end of my senior year, I'd certified as a pharmacy technician. After graduation, I stepped into a good job and started college without having to borrow much money. Now, I might go on to become a pharmacist!

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

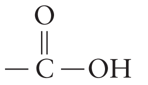
Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Assign IUPAC names and draw structural formulas for carboxylic acids. **(Section 15.1)**
2. Explain how hydrogen bonding affects the physical properties of carboxylic acids. **(Section 15.2)**
3. Recognize and write key reactions of carboxylic acids. **(Section 15.3)**
4. Assign common and IUPAC names to carboxylic acid salts. **(Section 15.4)**
5. Describe uses for carboxylate salts. **(Section 15.4)**
6. Recognize and write key reactions for ester formation. **(Section 15.5)**
7. Assign common and IUPAC names to esters. **(Section 15.6)**
8. Recognize and write key reactions of esters. **(Section 15.7)**
9. Write reactions for the formation of phosphate esters. **(Section 15.8)**

THE TART FLAVOR of foods that taste sour is generally caused by the presence of one or more carboxylic acids. Vinegar contains acetic acid, lemons and other citrus fruits contain citric acid (see **Figure 15.1**), and the tart taste of apples is caused by malic acid.

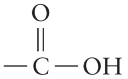
The characteristic functional group of **carboxylic acids** is the **carboxyl group:**



$$-\overset{\overset{\displaystyle O}{\|}}{C}-OH \qquad -COOH \quad \text{or} \quad -CO_2H$$

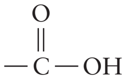
carboxyl group   abbreviated forms

carboxylic acid An organic compound that contains the



$-\overset{\overset{\displaystyle O}{\|}}{C}-OH$ functional group.

carboxyl group The



$-\overset{\overset{\displaystyle O}{\|}}{C}-OH$ group.

Carboxyl-containing compounds are found abundantly in nature (see **Figure 15.2**). Examples are lactic acid, which is formed in muscle cells during vigorous exercise, and citric acid, which is an important intermediate in cellular energy production, as well as a flavoring agent in citrus fruits (see **Table 15.1**).

© Mark Slabaugh

FIGURE 15.1 Citrus fruits and juices are rich in citric acid. What flavor sensation is characteristic of acids?

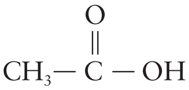
© Mark Slabaugh

FIGURE 15.2 Rhubarb and spinach contain oxalic acid, a compound with two carboxyl groups. The nomenclature of dicarboxylic acids is not discussed here. What would you propose as the IUPAC ending for molecules with two carboxyl groups?

15.1 The Nomenclature of Carboxylic Acids

Learning Objective 1 Assign IUPAC names and draw structural formulas for carboxylic acids.

Because of their abundance in nature, carboxylic acids were among the first organic compounds studied in detail. No systematic nomenclature system was then available, so the acids were usually named after some familiar source. Acetic acid,



$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-OH$$

acetic acid

the sour constituent in vinegar (see **Figure 15.3**), is named after *acetum*, the Latin word for vinegar. Butyric acid occurs in rancid butter (the Latin word for butter is *butyrum*). Many of these common names are still widely used today (see **Table 15.1**). Carboxylic acids with long hydrocarbon chains, generally 12 to 20 carbon atoms, are called **fatty acids** (see **Chapter 18**) because they were first isolated from natural fats. These acids, such as stearic acid with 18 carbons, are known almost exclusively by their common names.

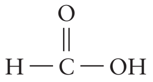
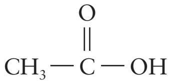
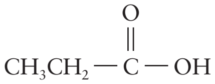
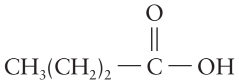
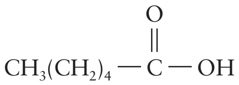
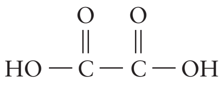
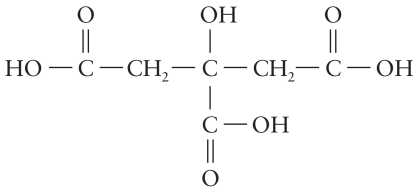
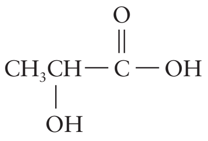
HEINZ
VINEGAR

© Cengage Learning/Charles D. Winters

FIGURE 15.3 Acetic acid is the active component in vinegar and a familiar laboratory weak acid.

fatty acid A long-chain carboxylic acid found in fats.

TABLE 15.1 Examples of Carboxylic Acids

Common Name	IUPAC Name	Structural Formula	Characteristics and Primary Uses
Formic acid	methanoic acid	 $\mathrm{H{-}\overset{\overset{O}{\|}}{C}{-}OH}$	Stinging agents of certain ants and nettles; used in food preservation
Acetic acid	ethanoic acid	 $\mathrm{CH_3{-}\overset{\overset{O}{\|}}{C}{-}OH}$	Active ingredient in vinegar; used in food preservation
Propionic acid	propanoic acid	 $\mathrm{CH_3CH_2{-}\overset{\overset{O}{\|}}{C}{-}OH}$	Salts used as mold inhibitors
Butyric acid	butanoic acid	 $\mathrm{CH_3(CH_2)_2{-}\overset{\overset{O}{\|}}{C}{-}OH}$	Odor-causing agent in rancid butter
Caproic acid	hexanoic acid	 $\mathrm{CH_3(CH_2)_4{-}\overset{\overset{O}{\|}}{C}{-}OH}$	Characteristic odor of Limburger cheese
Oxalic acid	ethanedioic acid	 $\mathrm{HO{-}\overset{\overset{O}{\|}}{C}{-}\overset{\overset{O}{\|}}{C}{-}OH}$	Present in leaves of some plants such as rhubarb and spinach; used as a cleaning agent for rust stains on fabric and porcelain
Citric acid	2-hydroxy-1,2,3-propanetricarboxylic acid	 $\mathrm{HO{-}\overset{\overset{O}{\|}}{C}{-}CH_2{-}\underset{\underset{\underset{\underset{O}{\|}}{C-OH}}{\vert}}{\overset{\overset{OH}{\vert}}{C}}{-}CH_2{-}\overset{\overset{O}{\|}}{C}{-}OH}$	Present in citrus fruits; used as a flavoring agent in foods; present in cells
Lactic acid	2-hydroxypropanoic acid	 $\mathrm{CH_3\underset{\underset{OH}{\vert}}{CH}{-}\overset{\overset{O}{\|}}{C}{-}OH}$	Found in sour milk and sauerkraut; formed in muscles during exercise

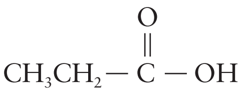
Dougal Waters/Stone/Getty Images

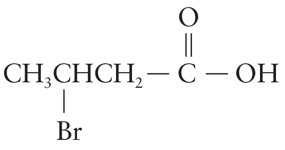
FIGURE 15.4 PABA (*p*-aminobenzoic acid) is a common ingredient in sunscreens. It absorbs ultraviolet (UV) radiation, protecting the skin from damage.

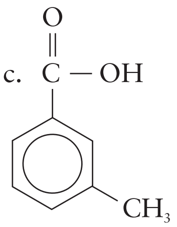
To name a carboxylic acid using the IUPAC system, the longest carbon chain including the carboxyl group is found and numbered. The numbering begins with the carboxyl carbon, so in monocarboxylic acids it is always located at the beginning of the chain, and no number is needed to locate it. The final *-e* of the parent hydrocarbon is dropped, and the ending *-oic* is added, followed by the word *acid*. Groups attached to the chain are named and located as before. Aromatic acids are given names derived from the parent compound, benzoic acid (see **Figure 15.4**).

Example 15.1 Naming Carboxylic Acids

Use IUPAC rules to name the following carboxylic acids:

a.  $\mathrm{CH_3CH_2{-}\overset{\overset{O}{\|}}{C}{-}OH}$

b.  $\mathrm{CH_3\underset{\underset{Br}{\vert}}{CH}CH_2{-}\overset{\overset{O}{\|}}{C}{-}OH}$

c. 

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Solution

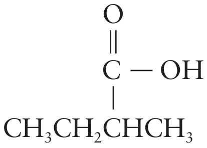
a. The carbon chain contains three carbons including the functional group carbon. Thus, the name is based on the parent hydrocarbon chain, propane. The carboxyl group is at position one, hence the name is propanoic acid.

b. The chain contains four carbon atoms, and a bromine is attached to carbon number 3. The name is 3-bromobutanoic acid.

c. The aromatic acids are named as derivatives of benzoic acid. The carboxyl group is at position one, and the acid name is 3-methylbenzoic acid.

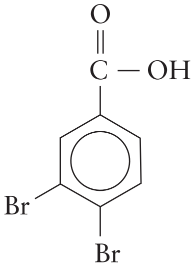
✔ **LEARNING CHECK 15.1** Give the IUPAC name to the following:

a.



$$CH_3CH_2\overset{\overset{\overset{O}{\|}}{C}-OH}{\overset{|}{C}H}CH_3$$

b.



15.2 Physical Properties of Carboxylic Acids

Learning Objective 2 Explain how hydrogen bonding affects the physical properties of carboxylic acids.

Carboxylic acids with low molecular weights are liquids at room temperature and have characteristically sharp or unpleasant odors (see **Table 15.2**). Butyric acid, for example, is a component of perspiration and is partially responsible for the odor of locker rooms and unwashed socks. As the molecular weight of carboxylic acids increases, so does the boiling point. The heavier acids (containing more than 10 carbons) are waxlike solids. Stearic acid ($C_{18}H_{36}O_2$), for example, is mixed with paraffin to produce a wax used to make candles.

TABLE 15.2 Physical Properties of Some Carboxylic Acids

Common Name	Structural Formula	Boiling Point (°C)	Melting Point (°C)	Solubility (g/100 mL H_2O)
Formic acid	H—COOH	101	8	Infinite
Acetic acid	CH_3—COOH	118	17	Infinite
Propionic acid	CH_3—CH_2—COOH	141	−21	Infinite
Butyric acid	CH_3—$(CH_2)_2$—COOH	164	−5	Infinite
Valeric acid	CH_3—$(CH_2)_3$—COOH	186	−34	5
Caproic acid	CH_3—$(CH_2)_4$—COOH	205	−3	1
Caprylic acid	CH_3—$(CH_2)_6$—COOH	239	17	Insoluble
Capric acid	CH_3—$(CH_2)_8$—COOH	270	32	Insoluble
Lauric acid	CH_3—$(CH_2)_{10}$—COOH	299	44	Insoluble
Myristic acid	CH_3—$(CH_2)_{12}$—COOH	Decomposes	58	Insoluble
Palmitic acid	CH_3—$(CH_2)_{14}$—COOH	Decomposes	63	Insoluble
Stearic acid	CH_3—$(CH_2)_{16}$—COOH	Decomposes	71	Insoluble

When boiling points of compounds with similar molecular weights are compared, the carboxylic acids have the highest boiling points of any organic compounds we have studied so far. See **Table 15.3** and **Figure 15.5**.

TABLE 15.3 **Boiling Points of Compounds with Similar Molecular Weight**

Class	Compound	Molecular Weight	Boiling Point (°C)
Alkane	pentane	72	35
Ether	diethyl ether	74	35
Aldehyde	butanal	72	76
Alcohol	1-butanol	74	118
Carboxylic acid	propanoic acid	74	141

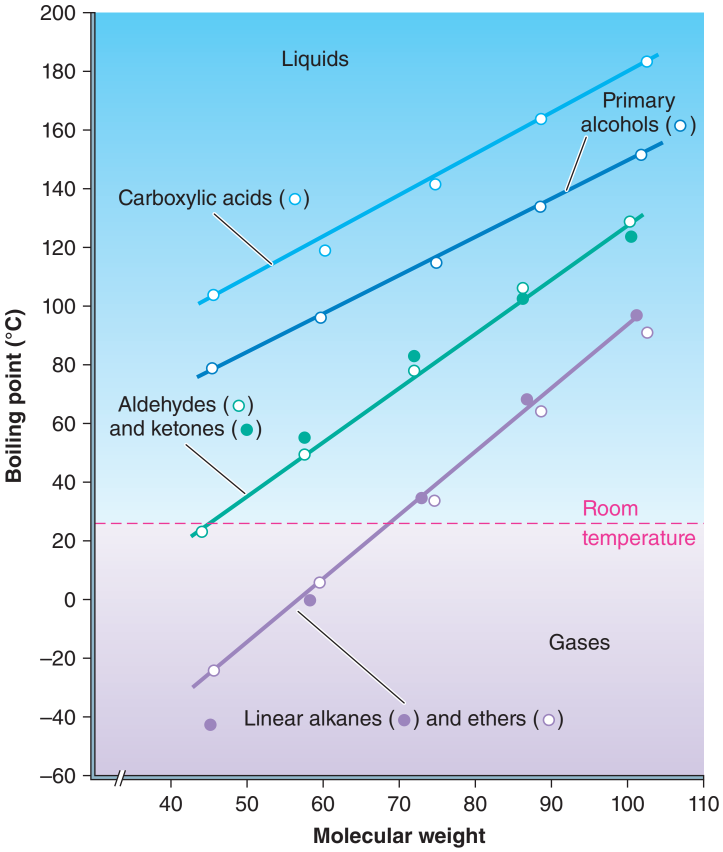
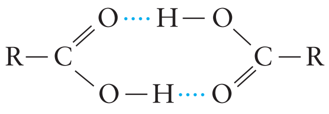


FIGURE 15.5 The boiling points of carboxylic acids are higher than those of all the other organic compounds studied thus far.

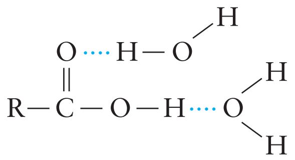
For simple aliphatic compounds, the boiling points usually increase in this order: hydrocarbons and ethers, aldehydes and ketones, alcohols, and carboxylic acids. Carboxylic acids, like alcohols, can form intermolecular hydrogen bonds. It is this bonding that causes high boiling points. Acids have higher boiling points than alcohols with similar molecular weights because hydrogen-bonded acids are held together by two hydrogen bonds rather than the one hydrogen bond that is characteristic of alcohols. A structure where two identical molecules are joined together is called a **dimer**:

dimer Two identical molecules bonded together.



Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Low-molecular-weight acids are very soluble in water (see **Table 15.2**) because of hydrogen bonds that are formed between the carboxyl group and water molecules (intermolecular hydrogen bonds). As the length of the nonpolar hydrocarbon portion (the R group) of the carboxylic acid increases, the water solubility decreases. Carboxylic acids containing eight or more carbon atoms are not appreciably soluble in water and are considered to be insoluble.



Organic compounds may be arranged according to increasing water solubility as follows: hydrocarbons, ethers, aldehydes and ketones, alcohols, and carboxylic acids. Because forces resulting from hydrogen bonding play important roles in determining both boiling points and water solubility, it is not surprising that the same order is generally observed for these two properties.

15.3 The Acidity of Carboxylic Acids

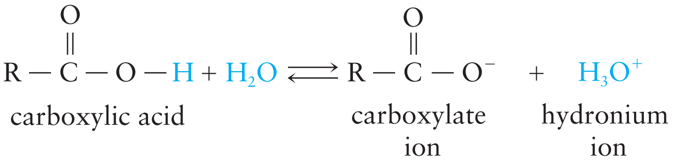
Learning Objective 3 Recognize and write key reactions of carboxylic acids.

carboxylate ion

The $R-\overset{\overset{\displaystyle O}{\|}}{C}-O^-$ ion that results from the dissociation of a carboxylic acid.

The most important chemical property of carboxylic acids is the acidic behavior implied by their name. The hydrogen attached to the oxygen of the carboxyl group gives carboxylic acids their acidic character (see **Figure 15.6**). In water, this proton may leave the acid, converting it into a **carboxylate ion**. Reaction 15.1 gives the general reaction, and Reaction 15.2 gives a specific example:

General reaction:



$$R-\overset{\overset{\displaystyle O}{\|}}{C}-O-H + H_2O \rightleftharpoons R-\overset{\overset{\displaystyle O}{\|}}{C}-O^- + H_3O^+ \qquad (15.1)$$

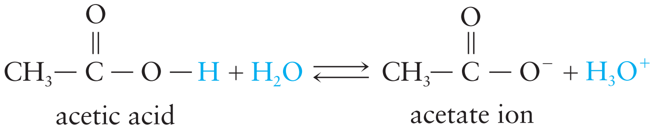
carboxylic acid — carboxylate ion — hydronium ion

Clarence Holmes Wildlife/Alamy Stock Photo

FIGURE 15.6 As a defensive action, formicine ants can spray formic acid (methanoic acid), which causes skin irritation because of its acidic properties.

Generally, carboxylic acids behave as weak acids (see **Figure 15.7**). A 1 M solution of acetic acid, for example, is only about 0.5% dissociated.

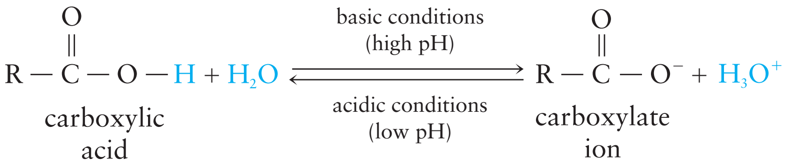
Specific example:



$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-O-H + H_2O \rightleftharpoons CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-O^- + H_3O^+ \qquad (15.2)$$

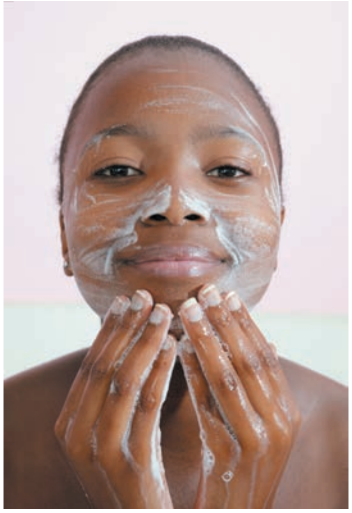
acetic acid — acetate ion

It is important to realize that Reactions 15.1 and 15.2 are reversible. According to Le Châtelier's principle, the addition of H_3O^+ (low pH) should favor formation of the carboxylic acid, and removal of H_3O^+ by adding base (high pH) should favor formation of the carboxylate ion:



$$R-\overset{\overset{\displaystyle O}{\|}}{C}-O-H + H_2O \underset{\text{acidic conditions (low pH)}}{\overset{\text{basic conditions (high pH)}}{\rightleftharpoons}} R-\overset{\overset{\displaystyle O}{\|}}{C}-O^- + H_3O^+ \qquad (15.3)$$

carboxylic acid — carboxylate ion



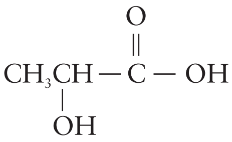
David Malan/Gallo Images ROOTS RF collection/Getty Images

FIGURE 15.7 A common component of facial cleansers is glycolic acid, which helps shed dead skin cells, revealing the newer, brighter layers underneath.

Thus, the pH of a solution determines the form in which a carboxylic acid exists in the solution. At pH 7.4, the normal pH of body fluids, the carboxylate form predominates. For example, citric acid in body fluids is often referred to as citrate. This is an important point for later chapters in biochemistry.

Example 15.2 Writing Carboxylate Structures

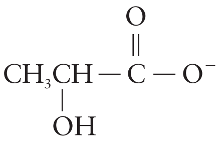
Lactic acid is formed in muscles during exercise. Draw the structure of the carboxylate form, lactate.



$$\mathrm{CH_3}\underset{\underset{\displaystyle\mathrm{OH}}{|}}{\mathrm{CH}}-\overset{\overset{\displaystyle\mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{OH}$$

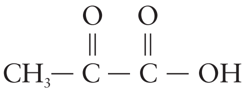
lactic acid

Solution



$$\mathrm{CH_3}\underset{\underset{\displaystyle\mathrm{OH}}{|}}{\mathrm{CH}}-\overset{\overset{\displaystyle\mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{O^-}$$

✔ **LEARNING CHECK 15.2** Pyruvic acid, an important intermediate in the energy-conversion reactions in living organisms, is usually called pyruvate because it is commonly in the carboxylate form. Draw the structure of pyruvate.

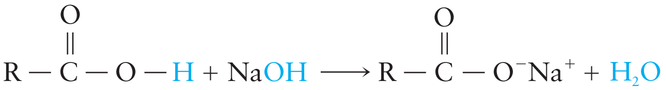


$$\mathrm{CH_3}-\overset{\overset{\displaystyle\mathrm{O}}{\|}}{\mathrm{C}}-\overset{\overset{\displaystyle\mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{OH}$$

pyruvic acid

Although they are weak, carboxylic acids react readily with strong bases such as sodium hydroxide or potassium hydroxide to form salts. Reaction 15.4 gives the general reaction, and Reactions 15.5 and 15.6 are two specific examples:

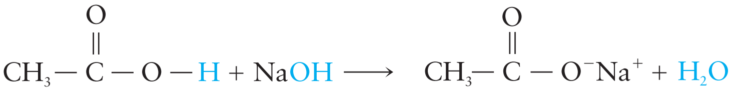
General reaction:



$$\mathrm{R}-\overset{\overset{\displaystyle\mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{O}-\mathrm{H}+\mathrm{NaOH}\longrightarrow \mathrm{R}-\overset{\overset{\displaystyle\mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{O^-Na^+}+\mathrm{H_2O} \qquad (15.4)$$

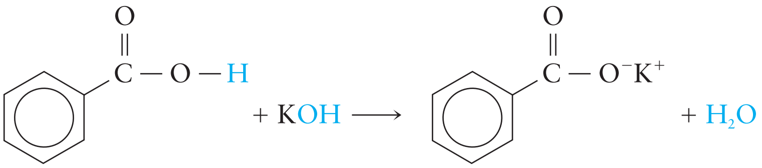
carboxylic acid sodium carboxylate

Specific examples:



$$\mathrm{CH_3}-\overset{\overset{\displaystyle\mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{O}-\mathrm{H}+\mathrm{NaOH}\longrightarrow \mathrm{CH_3}-\overset{\overset{\displaystyle\mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{O^-Na^+}+\mathrm{H_2O} \qquad (15.5)$$

acetic acid sodium acetate

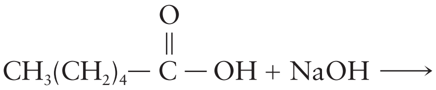


(15.6)

benzoic acid potassium benzoate

Example 15.3 Writing Reactions

Caproic acid (hexanoic acid) gives rise to the characteristic odor of Limburger cheese. Write the structural formulas for the products of the following reaction:

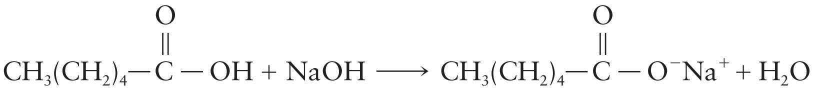


$$CH_3(CH_2)_4-\overset{O}{\overset{\|}{C}}-OH + NaOH \longrightarrow$$

caproic acid

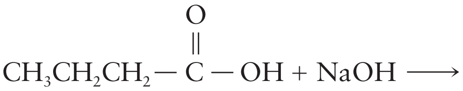
Solution

Using Reaction 15.4 as a guide:



$$CH_3(CH_2)_4-\overset{O}{\overset{\|}{C}}-OH + NaOH \longrightarrow CH_3(CH_2)_4-\overset{O}{\overset{\|}{C}}-O^-Na^+ + H_2O$$

✔ **LEARNING CHECK 15.3** Write the structural formulas for the products of the following reaction:



$$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-OH + NaOH \longrightarrow$$

15.4 Salts of Carboxylic Acids

Learning Objective 4 Assign common and IUPAC names to carboxylic acid salts.

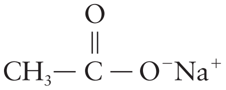
Learning Objective 5 Describe uses for carboxylate salts.

15.4A Nomenclature

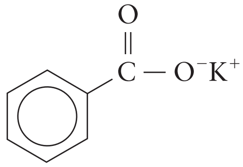
Both common names and IUPAC names are assigned to carboxylic acid salts by naming the metal first and changing the *-ic* ending of the acid name to *-ate*.

Example 15.4 Naming Salts

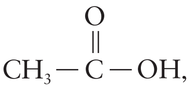
Give both a common name and an IUPAC name to the following salts:

a. 

$CH_3-\overset{O}{\overset{\|}{C}}-O^-Na^+$

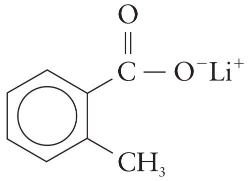
b. 

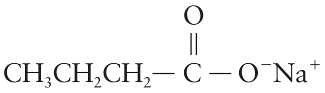
Solution

a. This salt is formed from  $CH_3-\overset{O}{\overset{\|}{C}}-OH$, which is called acetic acid (common name) or ethanoic acid (IUPAC name). Thus, the salt is sodium acetate (common name) or sodium ethanoate (IUPAC name).

b. This compound is the potassium salt of benzoic acid (both the common and IUPAC names). The name is potassium benzoate.

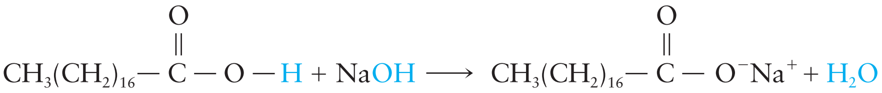
✔ LEARNING CHECK 15.4 Give the IUPAC name for the following salts:

a. 

b. 

$\mathrm{CH_3CH_2CH_2}-\overset{O}{\overset{\|}{C}}-O^-Na^+$

Carboxylic acid salts are solids at room temperature and are usually soluble in water because they are ionic. Even long-chain acids with an extensive nonpolar hydrocarbon portion can be solubilized by converting them into salts (Reaction 15.7):



$$\mathrm{CH_3(CH_2)_{16}}-\overset{O}{\overset{\|}{C}}-O-H + NaOH \longrightarrow \mathrm{CH_3(CH_2)_{16}}-\overset{O}{\overset{\|}{C}}-O^-Na^+ + H_2O \qquad (15.7)$$

stearic acid
(insoluble)

sodium stearate
(soluble)

15.4B Useful Carboxylic Acid Salts

A number of acid salts are important around the home. Sodium stearate ($CH_3(CH_2)_{16}COO^-Na^+$) and other sodium and potassium salts of long-chain carboxylic acids are used as soaps (see **Figure 15.8**).

Calcium and sodium propanoate are used commercially as preservatives in bread, cakes, and cheese to prevent the growth of bacteria and molds (see **Figure 15.9**). The parent acid, CH_3CH_2COOH, occurs naturally in Swiss cheese. The labels for these bakery products often contain the common name propionate, rather than the IUPAC-acceptable name propanoate.

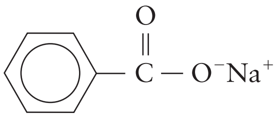
© Cengage Learning/Charles D. Winters

FIGURE 15.8 Soap products enable us to keep ourselves and our homes clean.

© Michael C. Slabaugh

FIGURE 15.9 Propanoates extend the shelf life of bread, preventing the formation of mold.

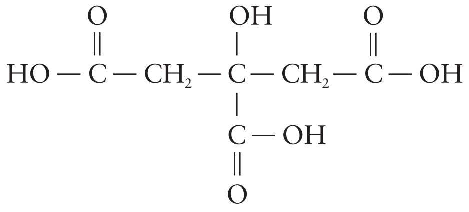
Sodium benzoate, another common food preservative, occurs naturally in many foods, especially cranberries and prunes. It is used in bakery products, ketchup, carbonated beverages, and a host of other foods:



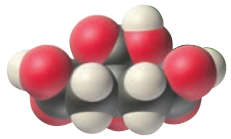
sodium benzoate

Zinc 10-undecylenate, the zinc salt of $CH_2=CH(CH_2)_8COOH$, is commonly used to treat athlete's foot. One commercial product that contains zinc 10-undecylenate is Desenex®.

A mixture of sodium citrate and citric acid



citric acid



Citric acid

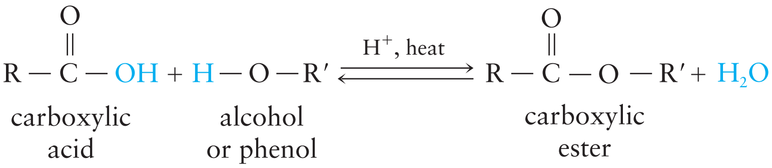
is widely used as a buffer to control pH. Products sold as foams or gels such as jelly, ice cream, candy, and whipped cream maintain their desirable characteristics only at certain pHs, which can be controlled by the citrate/citric acid buffer. This same buffer is used in medicines and in human blood that is used for transfusions. In blood, it also functions as an anticoagulant.

15.5 Carboxylic Esters

Learning Objective 6 Recognize and write key reactions for ester formation.

A very important reaction occurs when carboxylic acids are heated with alcohols or phenols in the presence of an acid catalyst. A molecule of water splits out and a **carboxylic ester** is formed.

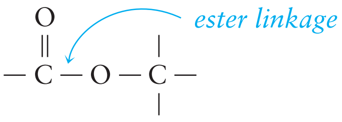
General reaction:



$$\mathrm{R-\overset{\overset{\displaystyle O}{\|}}{C}-OH + H-O-R' \xrightleftharpoons{H^+,\ heat} R-\overset{\overset{\displaystyle O}{\|}}{C}-O-R' + H_2O} \qquad (15.8)$$

carboxylic acid — alcohol or phenol — carboxylic ester

As before, R′ indicates that the two R groups can be the same or different. The process of ester formation is called **esterification**, and the carbonyl carbon–oxygen single bond of the ester group is called the **ester linkage**:



$$\mathrm{-\overset{\overset{\displaystyle O}{\|}}{C}-O-\overset{|}{\underset{|}{C}}-}$$

ester group

The ester functional group is a key structural feature in fats, oils, and other lipids (see **Chapter 18**). Also widely found in fruits and flowers, many esters are very fragrant and represent some of nature's most pleasant odors (see **Figure 15.10**). Because of this characteristic, esters are commonly used as flavoring agents in foods and as scents in personal products (see **Figure 15.11**).

carboxylic ester A compound with the $\mathrm{-\overset{\overset{\displaystyle O}{\|}}{C}-OR}$ functional group.

esterification The process of forming an ester.

ester linkage The carbonyl carbon–oxygen single bond of the ester group.

© Mark Slabaugh

FIGURE 15.10 Esters are partially responsible for the fragrance of oranges, pears, bananas, pineapples, and strawberries.

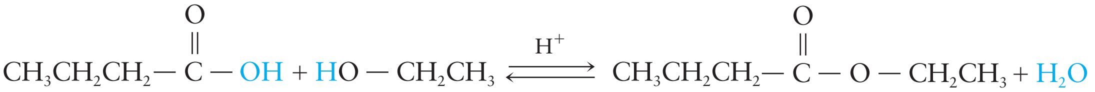
Keith Homan/Shutterstock.com

Gabriela Beres/Shutterstock.com

FIGURE 15.11 Esters are common in familiar flavorings. (a) Grape flavoring, the ester methyl anthranilate, is added to children's Tylenol to make it tastier. (b) Methyl salicylate, present in wintergreen, has analgesic and anti-inflammatory properties as well as a unique flavor.

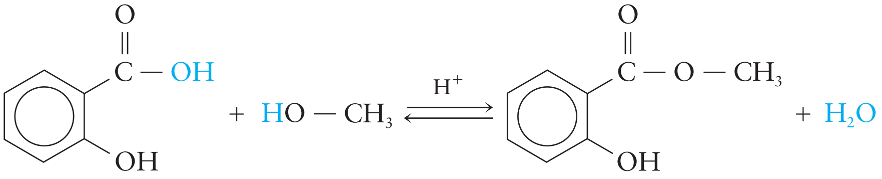
Reactions 15.9 and 15.10 illustrate the formation of two widely used esters.

Specific examples:



$$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-OH + HO-CH_2CH_3 \xrightleftharpoons{H^+} CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3 + H_2O \qquad (15.9)$$

butanoic acid ethyl alcohol ethyl butanoate (strawberry flavoring)

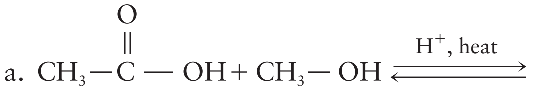


(15.10)

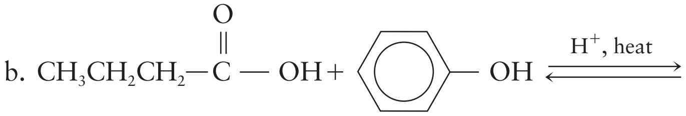
salicylic acid methyl alcohol methyl salicylate (oil of wintergreen)

Example 15.5 Showing Ester Formation

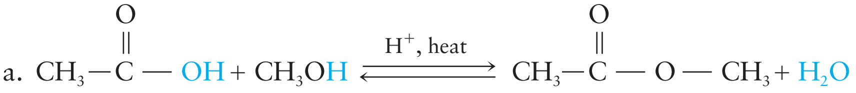
Give the structure of the ester formed in the following reactions:



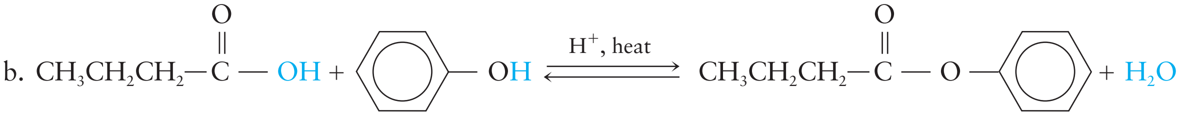
a. $CH_3-\overset{O}{\overset{\|}{C}}-OH + CH_3-OH \xrightleftharpoons{H^+,\ heat}$



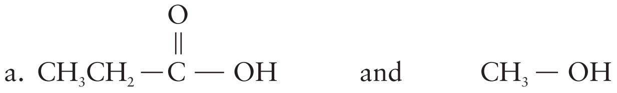
Solution



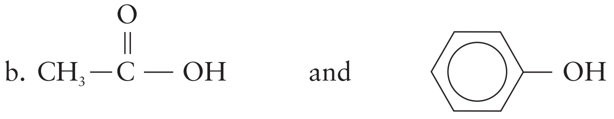
a. $CH_3-\overset{O}{\overset{\|}{C}}-OH + CH_3OH \xrightleftharpoons{H^+,\ heat} CH_3-\overset{O}{\overset{\|}{C}}-O-CH_3 + H_2O$

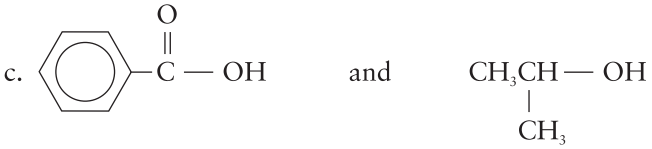


✔ LEARNING CHECK 15.5 Give the structure of the products formed in the following reactions:



a. $CH_3CH_2-\overset{O}{\overset{\|}{C}}-OH$ and CH_3-OH





ENVIRONMENTAL CONNECTIONS **15.1**

Plastics: Cleanup Time

Plastics, such as polyethylene terephthalate (PET), are versatile, inexpensive, and durable. They are used in medical devices, bicycle helmets, cell phones, and in other electronic equipment that makes modern life possible. Strong, lightweight plastics are used in thousands of ways to make our lives better.

The chemical structure of most plastics renders them resistant to many natural processes of degradation. The very properties that contribute to the value of plastics, such as insolubility in water and durability, lead to pollution of the Earth's ecosystems, especially its waterways and oceans. It is estimated that 1.1 million to 8.8 million tons of plastic waste enters the ocean from coastal communities each year. The Great Pacific Garbage Patch is one of five plastic accumulation zones in the world's oceans. It is believed to cover an area twice the size of Texas. Microplastics are widely distributed around the world and have been detected in bottled drinking water.

To address the problem of plastic pollution in the world's oceans, a Dutch organization, The Ocean Cleanup, is conducting trials with new, high-technology ships, essentially floating trash collectors. The Ocean Cleanup has also given attention to rivers after the realization that most ocean plastic comes from polluted rivers.

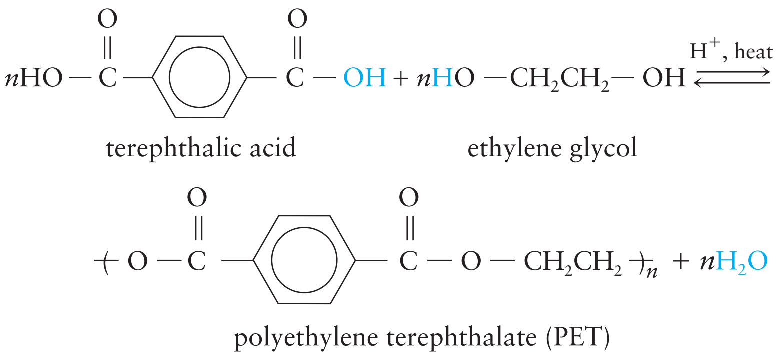
The *Interceptor* is a solar-powered trash-collecting barge, which collects plastic trash as it floats down rivers and before it enters the sea. A floating arm extends into the river's current to catch plastic and direct it into the ship's maw, where it can be stored for recycling. The idea is to implement ships like the *Interceptor* as a scalable solution to help meet the challenges of curbing plastic pollution.

COVER Images/ZUMA Press/Newscom

The *Interceptor*.

Polyesters, which are found in many consumer products, are just what the name implies—polymers made by an esterification reaction. The process used is an example of **condensation polymerization**, in which monomers combine and form a polymer; a small molecule such as water is formed as well. This is in contrast to addition polymerization, in which all atoms of the alkene monomer are incorporated into the polymer (see **Section 12.4**). In many condensation polymerization reactions, each monomer has two functional groups so that the chain can grow from either end. A typical example is the reaction of terephthalic acid and ethylene glycol:

condensation polymerization The process by which monomers combine together, with the simultaneous elimination of a small molecule.



$$n\mathrm{HO-C(=O)-C_6H_4-C(=O)-OH} + n\mathrm{HO-CH_2CH_2-OH} \xrightleftharpoons{\mathrm{H^+,\ heat}} \mathrm{-\!\!\left(O-C(=O)-C_6H_4-C(=O)-O-CH_2CH_2\right)_{\!n}} + n\mathrm{H_2O} \qquad (15.11)$$

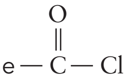
Molecules of product continue to react with available monomers until, finally, a polyester is formed with the general structure given above, where the *n* means that the unit in parentheses is repeated many times.

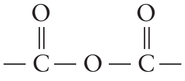
Over 3 billion pounds of the polyester PET are produced annually. Fibers are formed by melting the polymer and forcing the liquid through tiny holes in devices called spinnerettes. The resulting fibers are spun into thread or yarn and marketed under the trade names Dacron®, Fortrel®, and Terylene®, depending on the manufacturer. Typical uses include automobile tire cord and permanent-press clothing. In medicine, Dacron thread is used for sutures, and woven fabric is used to replace damaged or diseased sections of blood vessels and the esophagus. Dacron fibers are often blended with cotton to make a fabric that is more comfortable to wear on hot, humid days than those containing 100% polyester and that retains the latter's wrinkle resistance. Besides being forced through spinnerettes, PET melts may be forced through a narrow slit to produce thin sheets or films called Mylar® (see **Figure 15.12**).

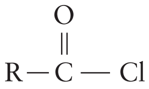
Bettmann/Getty Images

FIGURE 15.12 Mylar, a polyester developed by E. I. DuPont deNemours Co., was used to cover the wings and pilot's compartment of the *Gossamer Albatross*, the first human-powered aircraft to fly across the English Channel.

Although many esters can be prepared by the method just outlined in Reaction 15.8, the reversible nature of the reaction does not always allow for good yields of product. Two compounds that are more reactive than carboxylic acids and that produce esters in good yield are **carboxylic acid chlorides** and **carboxylic acid anhydrides**:

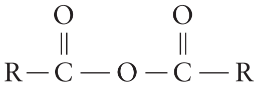
carboxylic acid chloride An organic compound that contains the  $-\overset{O}{\overset{\|}{C}}-Cl$ functional group.

carboxylic acid anhydride An organic compound that contains the  $-\overset{O}{\overset{\|}{C}}-O-\overset{O}{\overset{\|}{C}}-$ functional group.



$$R-\overset{O}{\overset{\|}{C}}-Cl$$

carboxylic acid
chloride

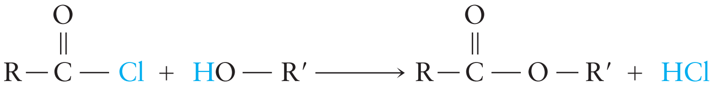


$$R-\overset{O}{\overset{\|}{C}}-O-\overset{O}{\overset{\|}{C}}-R$$

carboxylic acid
anhydride

These substances react vigorously with alcohols in a nonreversible manner.

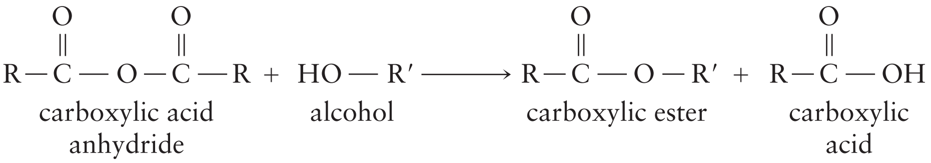
General reactions:



$$R-\overset{O}{\overset{\|}{C}}-Cl + HO-R' \longrightarrow R-\overset{O}{\overset{\|}{C}}-O-R' + HCl \tag{15.12}$$

carboxylic acid chloride — alcohol — carboxylic ester

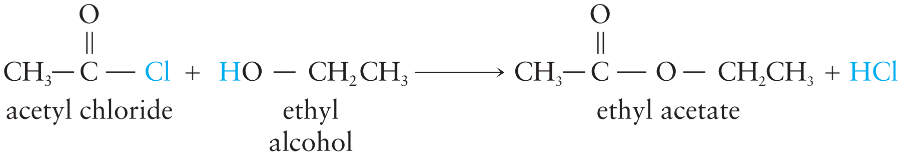
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.


carboxylic acid anhydride
alcohol
carboxylic ester
carboxylic acid

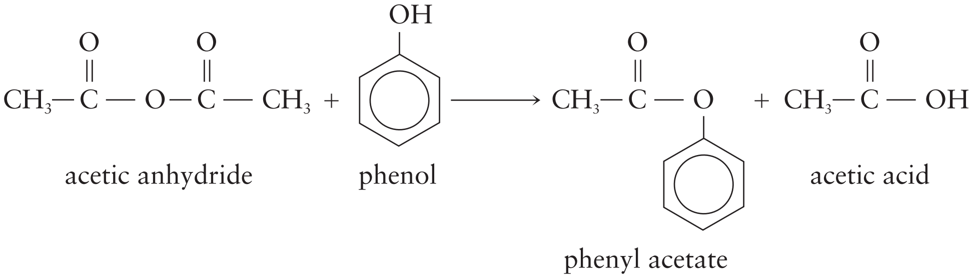
$$R-\overset{O}{\overset{\|}{C}}-O-\overset{O}{\overset{\|}{C}}-R + HO-R' \longrightarrow R-\overset{O}{\overset{\|}{C}}-O-R' + R-\overset{O}{\overset{\|}{C}}-OH \qquad (15.13)$$

Reactions 15.14 and 15.15 illustrate two specific examples. In another example, the laboratory synthesis of aspirin (Reaction 15.18), using acetic anhydride, gives excellent yields of the ester.

Specific reactions:


acetyl chloride
ethyl alcohol
ethyl acetate

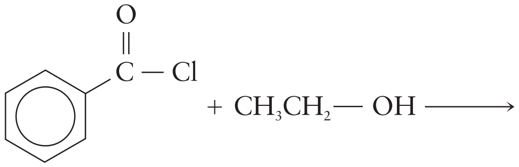
$$CH_3-\overset{O}{\overset{\|}{C}}-Cl + HO-CH_2CH_3 \longrightarrow CH_3-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3 + HCl \qquad (15.14)$$

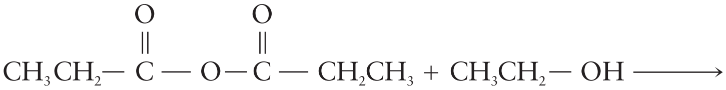

acetic anhydride
phenol
phenyl acetate
acetic acid

(15.15)

Example 15.6 Writing Structures for Ester Formation

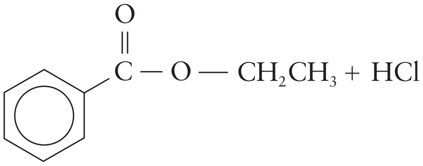
Give the structure of the ester formed in the following reactions:

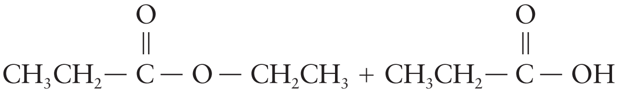
a. 

b. 

$$CH_3CH_2-\overset{O}{\overset{\|}{C}}-O-\overset{O}{\overset{\|}{C}}-CH_2CH_3 + CH_3CH_2-OH \longrightarrow$$

Solution

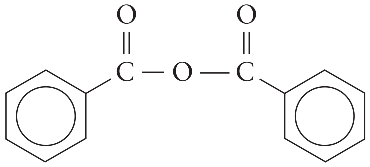
a. The products are 

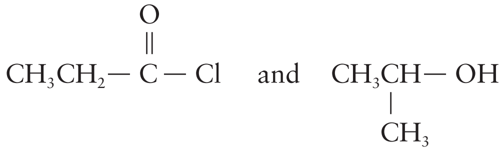
b. The products are 

$$CH_3CH_2-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3 + CH_3CH_2-\overset{O}{\overset{\|}{C}}-OH$$

The first product in each case is the ester.

✔ **LEARNING CHECK 15.6** Write equations to represent ester formation when the following pairs of compounds are reacted:

a.  and $CH_3—OH$

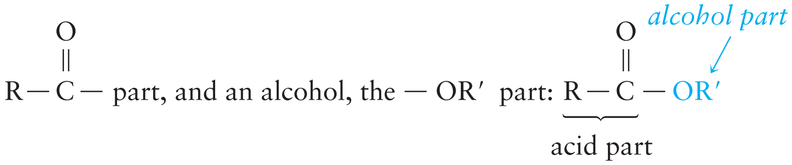
b. 

$$CH_3CH_2—\overset{\overset{\displaystyle O}{\|}}{C}—Cl \quad \text{and} \quad CH_3\underset{\underset{\displaystyle CH_3}{|}}{CH}—OH$$

15.6 The Nomenclature of Esters

Learning Objective 7 Assign common and IUPAC names to esters.

Esters are named by a common system as well as by IUPAC rules; the common names are used most often. It is helpful with both IUPAC and common names to think of the esters as being formed from a carboxylic acid, the

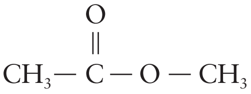


$$R—\overset{\overset{\displaystyle O}{\|}}{C}— \text{ part, and an alcohol, the } —OR' \text{ part: } \underbrace{R—\overset{\overset{\displaystyle O}{\|}}{C}}_{\text{acid part}}—\overset{\text{alcohol part}}{OR'}$$

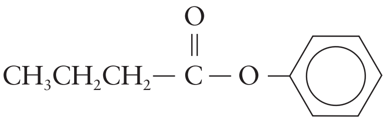
The first word of the name of an ester is the name of the alkyl or aromatic group (R′) contributed by the alcohol. The second word is the carboxylic acid name, with the *-ic acid* ending changed to *-ate*. This is similar to the method used for naming carboxylic acid salts. Thus, an ester of acetic acid becomes an acetate, one of butyric acid becomes a butyrate, one of lactic acid becomes a lactate, and so on.

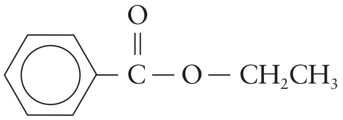
Example 15.7 Naming Esters

Give common and IUPAC names for the following esters:

a. 

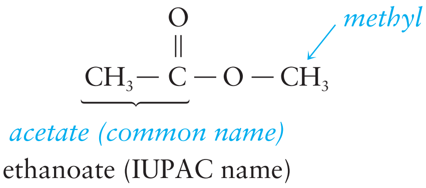
$$CH_3—\overset{\overset{\displaystyle O}{\|}}{C}—O—CH_3$$

b. 

c. 

Solution

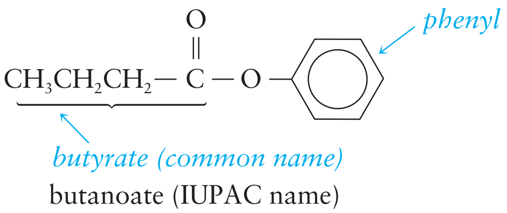
a. The first word is methyl, which refers to the alcohol portion:



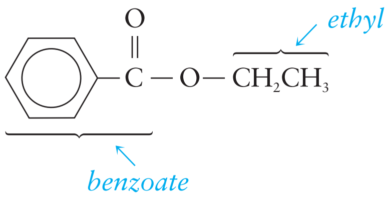
$$\underbrace{CH_3—\overset{\overset{\displaystyle O}{\|}}{C}}_{\substack{\text{acetate (common name)}\\ \text{ethanoate (IUPAC name)}}}—O—\overset{\text{methyl}}{CH_3}$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The second word is derived from the name of the two-carbon carboxylic acid (acetic acid or ethanoic acid). Thus, we have methyl acetate (common name) and methyl ethanoate (IUPAC name).

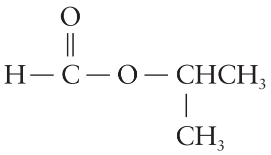
b.


Thus, the two names are phenyl butyrate (common name) and phenyl butanoate (IUPAC name).

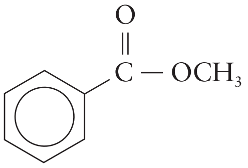
c.


Thus, we have ethyl benzoate (common name and IUPAC name).

✔ **LEARNING CHECK 15.7** Give both the common and the IUPAC names for each of the following esters:

a.


$$\mathrm{H-\overset{\overset{\displaystyle O}{\|}}{C}-O-\underset{\underset{\displaystyle CH_3}{|}}{CH}CH_3}$$

b.


15.7 Reactions of Esters

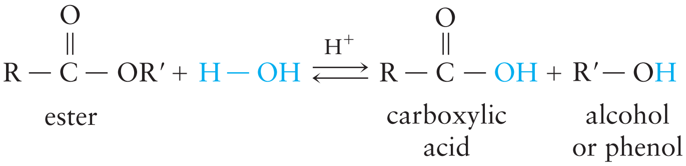
Learning Objective 8 Recognize and write key reactions of esters.

The most important reaction of carboxylic esters, both in commercial processes and in the body, involves the breaking of the ester linkage. The process is called either ester hydrolysis or saponification, depending on the reaction conditions.

15.7A Ester Hydrolysis

Ester hydrolysis is the reaction of an ester with water to break an ester linkage and produce an alcohol and a carboxylic acid. This process is simply the reverse of the esterification reaction (Reaction 15.8). Strong acids are frequently used as catalysts to hydrolyze esters.

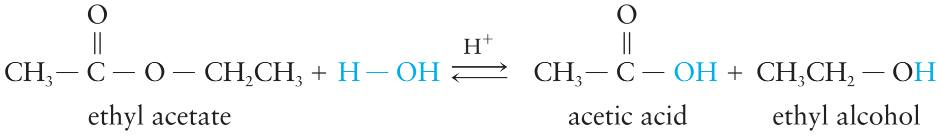
General reaction:



$$\underset{\text{ester}}{\mathrm{R-\overset{\overset{\displaystyle O}{\|}}{C}-OR'}} + \mathrm{H-OH} \xrightleftharpoons{H^+} \underset{\text{carboxylic acid}}{\mathrm{R-\overset{\overset{\displaystyle O}{\|}}{C}-OH}} + \underset{\text{alcohol or phenol}}{\mathrm{R'-OH}} \qquad (15.16)$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Specific example:



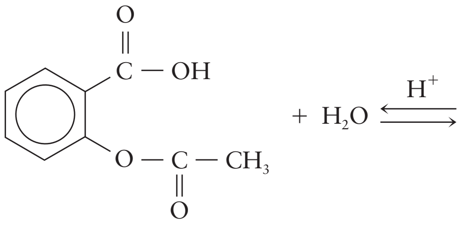
$$CH_3-\overset{\overset{O}{\|}}{C}-O-CH_2CH_3 + H-OH \xrightleftharpoons{H^+} CH_3-\overset{\overset{O}{\|}}{C}-OH + CH_3CH_2-OH \qquad (15.17)$$

Notice that when ester linkages break during hydrolysis, the elements of water (—OH and —H) are attached to the ester fragments to form the acid and alcohol (Reaction 15.16). The breaking of a bond and the attachment of the elements of water to the fragments are characteristic of all hydrolysis reactions.

The human body and other biological organisms are constantly forming and hydrolyzing a variety of esters. The catalysts used in these cellular processes are very efficient protein catalysts called enzymes (see **Chapter 20**). Animal fats and vegetable oils are esters. Their enzyme-catalyzed hydrolysis is an important process that takes place when they are digested.

Example 15.8 Writing Hydrolysis Reactions

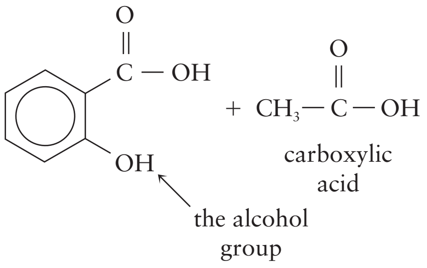
When aspirin enters the stomach, a hydrolysis reaction takes place. Give the structure of the products formed in the following reaction:



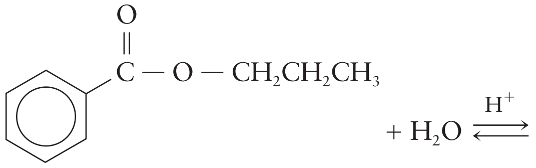
acetylsalicylic acid
(aspirin)

Solution

Using Key Reaction 15.16 as a guide, hydrolysis will produce an alcohol group and a carboxylic acid.



✔ **LEARNING CHECK 15.8** Give the structure of the products formed in the following hydrolysis reaction:



HEALTH CONNECTIONS **15.1**

Consider Low-Dose Aspirin

Aspirin, an ester of salicylic acid first prepared in 1893, is remarkably versatile. In the body it reduces fever but does not reduce normal body temperature. It also relieves a variety of simple pains such as headache, sprain, and toothache, and is an anti-inflammatory agent often used to treat arthritis.

Americans consume an estimated 80 billion aspirin tablets each year. The *Physicians' Desk Reference* lists more than 50 OTC (over-the-counter) drugs in which aspirin is the principal ingredient. Yet, despite the fact that aspirin has been in routine use for over a century, scientific journals continue to publish reports about new uses for this old remedy.

Aspirin interferes with the clotting action of blood by reducing the ability of platelets to clump together. A heart attack can result when a coronary artery that provides blood to the heart is blocked by a blood clot. Studies suggest that aspirin use can help prevent heart attacks and strokes due to blood clots in at-risk individuals. One study shows that aspirin reduces the chances of having a second heart attack by more than 30%.

The same process that reduces blood clotting is also responsible for some of the undesirable side effects of using aspirin. Aspirin use causes increased rates of gastrointestinal bleeding and hemorrhagic stroke (stroke caused by a ruptured blood vessel in the brain). Heavy aspirin use before surgery can present a danger because it increases the risk of severe bleeding after the operation.

If you've had a heart attack or stroke or have a high risk of having a first heart attack, your doctor may recommend you take a daily aspirin, unless you have a history of bleeding. When such therapy is recommended, a low dose of 81 mg per day (one baby aspirin) is generally used. Because the long-term, regular use of aspirin poses risks of serious bleeding, the decision to begin such a program should be made only after consultation with a physician.

ADULT ASPIRIN REGIMEN
ST. JOSEPH
LOW DOSE ASPIRIN
SAFETY COATED†
PAIN RELIEVER (NSAID)
81mg
AMERICA'S ASPIRIN
DOCTOR RECOMMENDED
100 YEARS
Enteric Coated
120 Micro** Tablets

Digitalreflections/Shutterstock.com

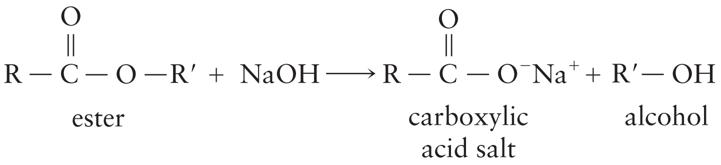
A variety of aspirin products is available.

15.7B Saponification

Like ester hydrolysis, **saponification** results in a breaking of the ester linkage and produces an alcohol and a carboxylic acid (see **Section 18.4** for more on saponification). However, unlike ester hydrolysis, saponification is done in solutions containing strong bases such as potassium or sodium hydroxide. The carboxylic acid is converted to a salt under these basic conditions.

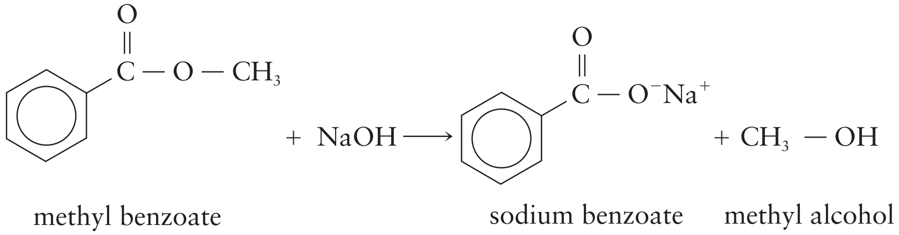
saponification The basic cleavage of an ester linkage.

General reaction:



$$R-\overset{\overset{\displaystyle O}{\|}}{C}-O-R' + NaOH \longrightarrow R-\overset{\overset{\displaystyle O}{\|}}{C}-O^{-}Na^{+} + R'-OH \qquad (15.18)$$

Specific example:

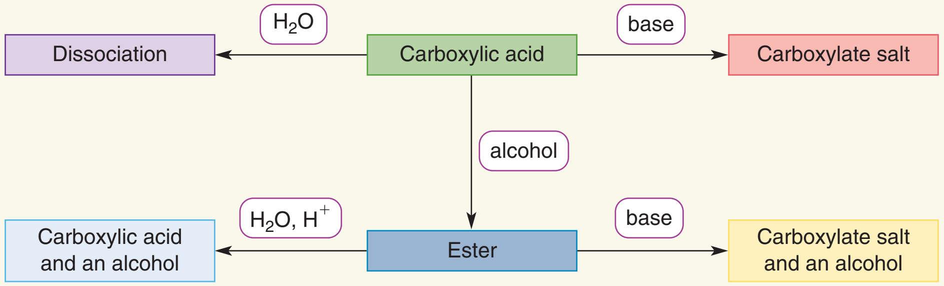


(15.19)

STUDY TOOLS 15.1

A Reaction Map for Carboxylic Acids

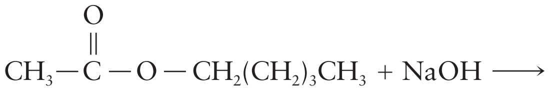
We hope you have become familiar with the reaction maps of Chapters 12, 13, and 14 and have found them useful in solving problems. Another reaction map is given below. It includes the key reactions of this chapter and should be useful as you answer questions and prepare for exams.



We will see in **Chapter 18** that saponification of fats and oils is important in the production of soaps.

Example 15.9 Writing Saponification Reactions

The ester pentyl ethanoate gives rise to the odor of bananas. Give structural formulas for the products of the following saponification reaction.

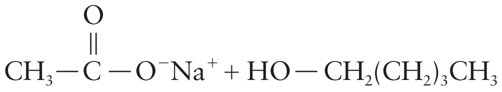


$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-O-CH_2(CH_2)_3CH_3 + NaOH \longrightarrow$$

pentyl ethanoate

Solution

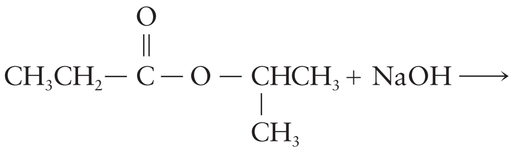
Using Key Reaction 15.18 as a guide, the products will be a carboxylate salt and an alcohol.



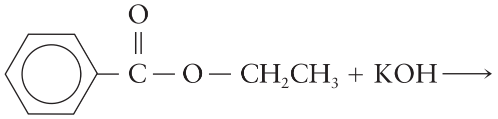
$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-O^-Na^+ + HO-CH_2(CH_2)_3CH_3$$

salt alcohol

✔ **LEARNING CHECK 15.9** Give structural formulas for the products of the following saponification reactions.

a. 

$$CH_3CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-O-\underset{\underset{\displaystyle CH_3}{|}}{CH}CH_3 + NaOH \longrightarrow$$

b. 

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

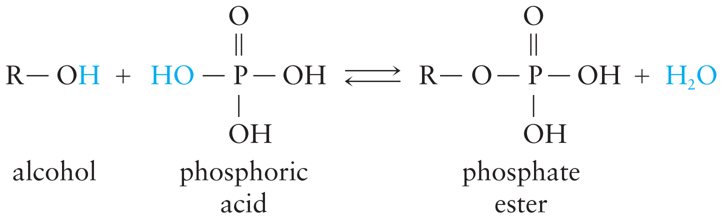
15.8 Esters of Inorganic Acids

Learning Objective 9 Write reactions for the formation of phosphate esters.

We have defined a carboxylic ester as the product of a reaction between a carboxylic acid and an alcohol. Alcohols can also form **esters** by reacting with inorganic acids such as sulfuric, nitric, and phosphoric acids. The most important of these in biochemistry are the esters of phosphoric acid (H_3PO_4).

ester A compound in which the —OH of an acid is replaced by an —OR.

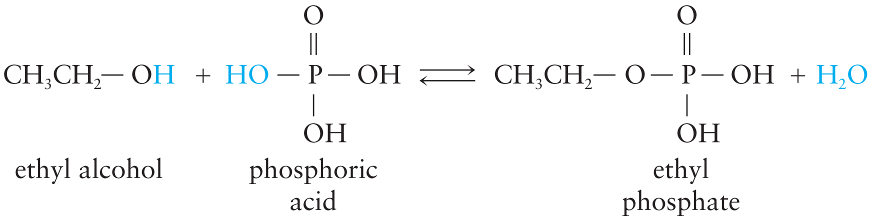
General reaction:



$$R{-}OH + HO{-}\underset{\displaystyle OH}{\overset{\displaystyle O}{\overset{\Vert}{\underset{|}{P}}}}{-}OH \rightleftharpoons R{-}O{-}\underset{\displaystyle OH}{\overset{\displaystyle O}{\overset{\Vert}{\underset{|}{P}}}}{-}OH + H_2O \qquad (15.20)$$

alcohol
phosphoric acid
phosphate ester

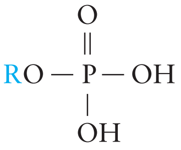
Specific example:



$$CH_3CH_2{-}OH + HO{-}\underset{\displaystyle OH}{\overset{\displaystyle O}{\overset{\Vert}{\underset{|}{P}}}}{-}OH \rightleftharpoons CH_3CH_2{-}O{-}\underset{\displaystyle OH}{\overset{\displaystyle O}{\overset{\Vert}{\underset{|}{P}}}}{-}OH + H_2O \qquad (15.21)$$

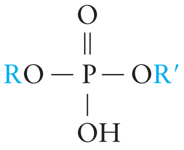
ethyl alcohol
phosphoric acid
ethyl phosphate

Because phosphoric acid has three —OH groups, it can form mono-, di-, and triesters:



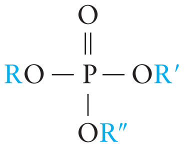
$$RO{-}\underset{\displaystyle OH}{\overset{\displaystyle O}{\overset{\Vert}{\underset{|}{P}}}}{-}OH$$

monoester,
one R group



$$RO{-}\underset{\displaystyle OH}{\overset{\displaystyle O}{\overset{\Vert}{\underset{|}{P}}}}{-}OR'$$

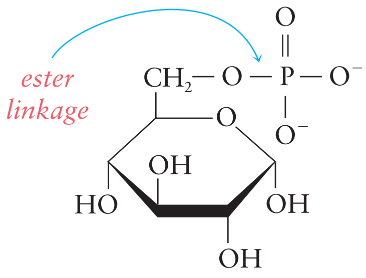
diester,
two R groups



$$RO{-}\underset{\displaystyle OR''}{\overset{\displaystyle O}{\overset{\Vert}{\underset{|}{P}}}}{-}OR'$$

triester,
three R groups

Mono- and diesters are essential to life and represent some of the most important biological molecules. An example of an important monoester is glucose-6-phosphate, which represents the first intermediate compound formed when glucose is oxidized to supply energy for the body (see **Chapter 23**):

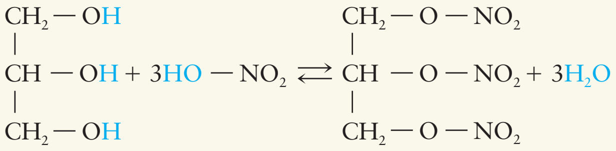


glucose-6-phosphate

HEALTH CONNECTIONS **15.2**

Nitroglycerin in Dynamite and in Medicine

Nitroglycerin is a nitrate ester resulting from the reaction of nitric acid and glycerol:



$$\begin{array}{l} CH_2-OH \\ | \\ CH-OH \\ | \\ CH_2-OH \end{array} + 3HO-NO_2 \rightleftarrows \begin{array}{l} CH_2-O-NO_2 \\ | \\ CH-O-NO_2 \\ | \\ CH_2-O-NO_2 \end{array} + 3H_2O$$

glycerol nitric acid nitroglycerin

First made in 1846 by the Italian chemist Sobrero, nitroglycerin was discovered to be a powerful explosive with applications in both war and peace. However, as a shock-sensitive, unstable liquid, nitroglycerin proved to be extremely dangerous to manufacture and handle. The Swedish chemist Alfred Nobel later perfected its synthesis and devised a safe method for handling it. Nobel mixed nitroglycerin with a clay-like absorbent material. The resulting solid, called dynamite, is an explosive that is much less sensitive to shock than liquid nitroglycerin. Dynamite is still one of the most important explosives used for mining, digging tunnels, and blasting hills for road building.

Surprising as it may seem, nitroglycerin is also an effective medicine. It is used to treat patients with angina pectoris—sharp chest pains caused by an insufficient supply of oxygen to the heart muscle. Angina pectoris is usually found in patients with coronary artery diseases, such as arteriosclerosis (hardening of the arteries). During overexertion or excitement, the partially clogged coronary arteries prevent the heart from getting an adequate supply of oxygenated blood, and pain results. Nitroglycerin relaxes the cardiac muscle and causes a dilation of the arteries, thus increasing blood flow to the heart and relieving the chest pains.

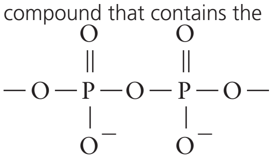
Van D. Bucher/Science Source

A transdermal patch allows nitroglycerin to be absorbed through the skin.

At body pH, the two —OH groups of the phosphoric acid are ionized, and the phosphate group has a charge of 2^-. Examples of important diesters include the phospholipids (see **Chapter 18**) and the nucleic acids (see **Chapter 21**).

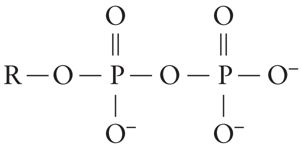
As we study key compounds in the storage and transfer of chemical energy in living systems (see **Chapter 22**), we will encounter phosphate esters in which two or three phosphate groups are linked. These **phosphoric anhydrides** are referred to as diphosphates and triphosphates.

phosphoric anhydride A compound that contains the



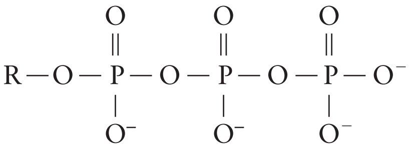
$$\begin{array}{c} \quad O \qquad\quad O \\ \quad \| \qquad\quad \| \\ -O-P-O-P-O- \\ \quad | \qquad\quad | \\ \quad O^- \qquad O^- \end{array}$$

group.



$$\begin{array}{c} \quad\quad O \qquad\quad O \\ \quad\quad \| \qquad\quad \| \\ R-O-P-O-P-O^- \\ \quad\quad | \qquad\quad | \\ \quad\quad O^- \qquad O^- \end{array}$$

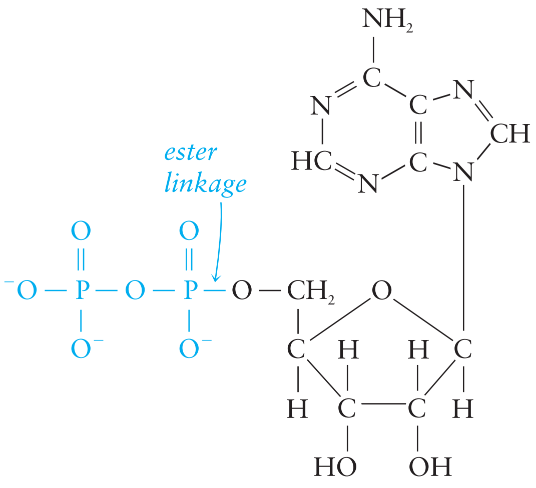
a diphosphate ester



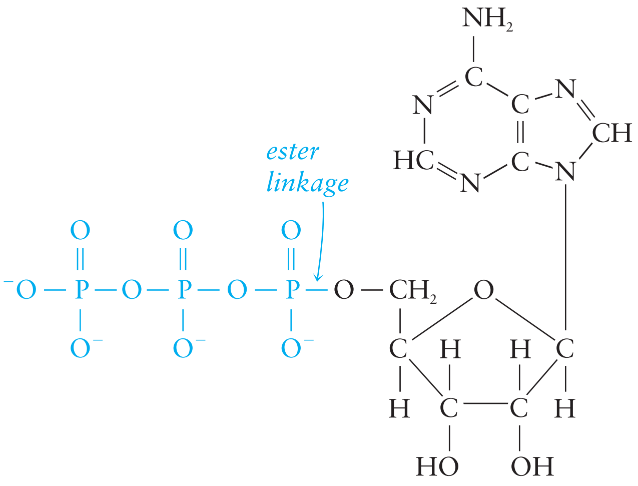
$$\begin{array}{c} \quad\quad O \qquad\quad O \qquad\quad O \\ \quad\quad \| \qquad\quad \| \qquad\quad \| \\ R-O-P-O-P-O-P-O^- \\ \quad\quad | \qquad\quad | \qquad\quad | \\ \quad\quad O^- \qquad O^- \qquad O^- \end{array}$$

a triphosphate ester

Adenosine diphosphate (ADP) and adenosine triphosphate (ATP) are the most important of these compounds. We will study their rather complex structures in more detail in **Section 22.7**. For now, note the ester linkages in each structure and the presence of the di- and triphosphate groups. Again, at the pH of body fluids, the —OH groups attached to the phosphorus lose H^+ and acquire negative charges.



ADP



ATP

Health Career Description

PHARMACY TECHNICIAN

Pharmacy technicians work under the supervision of pharmacists in a variety of settings. They may work in a traditional "drug-store" type pharmacy, a pharmacy within a "big box store," an online pharmacy, or a pharmacy within a hospital or clinic. Their time spent in customer interaction depends on the location of their work.

Pharm techs that work in stores or stand-alone pharmacies will serve as a liaison between the pharmacist and the public, answering questions about medications, store hours, insurance coverage, etc. Those who work in a hospital setting will be more involved in compounding medications or making sure medications are correctly matched to patients.

Pharm techs are expected to perform office duties and must have excellent computer and organizational skills. They manage inventories, stock machines and organize orders, and collect payments. They have a high level of responsibility because there is no room for error in a pharmacy practice.

Pharmacists depend on pharmacy techs to keep their businesses running smoothly and to provide an extra level of safety by checking that orders are filled and delivered correctly. Pharmacy technicians are not expected to have the same education level or understanding of chemistry and medications that pharmacists have, but they are expected to have a working understanding of pharmaceuticals so as to operate safely within the pharmacy industry.

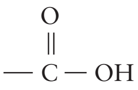
According to the Bureau of Labor Statistics, the median salary for a pharmacy technician with an associate degree is $32,000 per year and the field is expected to grow at a rate of 7% annually. This is a career that is well suited to people with an interest in pharmaceuticals, who enjoy interacting with people, and who want to help others.

Concept Summary

15.1 The Nomenclature of Carboxylic Acids

Learning Objective: Can you assign IUPAC names and draw structural formulas for carboxylic acids?

- The characteristic functional group of carboxylic acids is the carboxyl group.



$$-\overset{\overset{\displaystyle O}{\|}}{C}-OH$$

- Many of the simpler carboxylic acids are well known by common names.
- In the IUPAC system, the ending of *-oic acid* is used in the names of these compounds.
- Aromatic acids are named as derivatives of benzoic acid.

15.2 Physical Properties of Carboxylic Acids

Learning Objective: Can you explain how hydrogen bonding affects the physical properties of carboxylic acids?

- At room temperature, low-molecular-weight carboxylic acids are liquids with distinctively sharp or unpleasant odors.
- High-molecular-weight, long-chain acids are waxlike solids.
- Carboxylic acids are quite effective in forming dimers, two molecules held together by hydrogen bonds.
- Thus, they have relatively high boiling points, and those with lower molecular weights are soluble in water.

15.3 The Acidity of Carboxylic Acids

Learning Objective: Can you recognize and write key reactions of carboxylic acids?

- Soluble carboxylic acids behave as weak acids.
- They dissociate only slightly in water to form an equilibrium mixture with the carboxylate ion.
- The equilibrium concentrations of the carboxylic acid and the carboxylate ion depend on pH.
- At low pH, the acid form predominates, and at pH 7.4 (the pH of cellular fluids) and above, the carboxylate ion predominates.
- Carboxylic acids react with bases to produce carboxylate salts and water.

15.4 Salts of Carboxylic Acids

Learning Objective: Can you assign common and IUPAC names to carboxylic acid salts? Can you describe uses for carboxylate salts?

- The carboxylate salts are named by changing the *-ic* ending of the acid to *-ate*.
- The ionic nature of the salts makes them water soluble.
- A number of carboxylate salts are useful as food preservatives, soaps, and medicines.

15.5 Carboxylic Esters

Learning Objective: Can you recognize and write key reactions for ester formation?

- Carboxylic acids, acid chlorides, and acid anhydrides react with alcohols to produce esters.
- Polyesters result from the reaction of dicarboxylic acids and diols.
- Polyesters are an example of condensation polymers.
- These are produced when monomers react to form a polymer plus a small molecule such as water.
- Many esters are very fragrant and represent some of nature's most pleasant odors.
- Because of this characteristic, esters are widely used as flavoring agents.

15.6 The Nomenclature of Esters

Learning Objective: Can you assign common and IUPAC names to esters?

- Both common and IUPAC names for esters are formed by first naming the alkyl group of the alcohol portion followed by the name of the acid portion in which the *-ic acid* ending has been changed to *-ate*.

15.7 Reactions of Esters

Learning Objective: Can you recognize and write key reactions of esters?

- Esters can be converted back to carboxylic acids and alcohols under either acidic or basic conditions.
- Hydrolysis, the reaction with water in the presence of an acid, produces the carboxylic acid and alcohol.
- Saponification occurs in the presence of a base to produce the carboxylate salt and alcohol.

15.8 Esters of Inorganic Acids

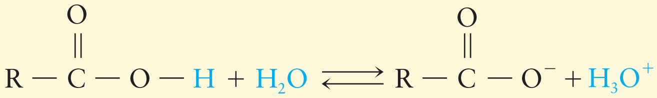
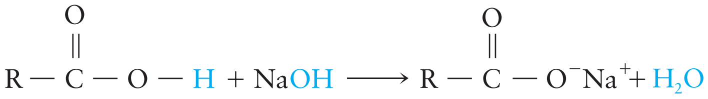
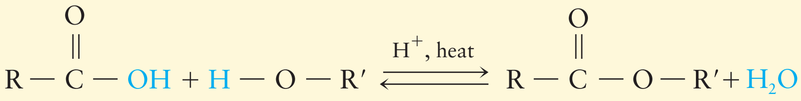
Learning Objective: Can you write reactions for the formation of phosphate esters?

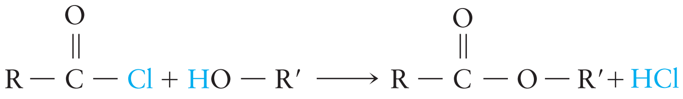
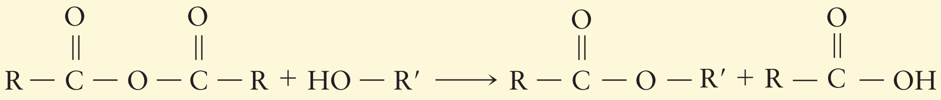
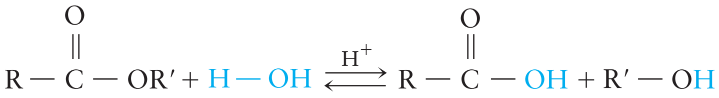
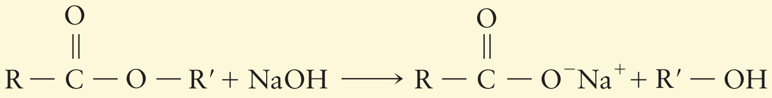
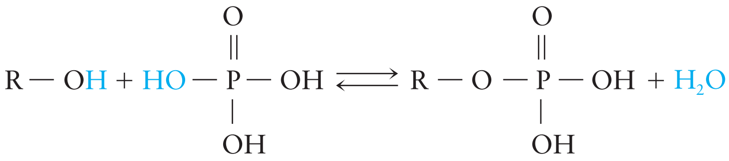
- Alcohols can also form esters by reacting with inorganic acids such as phosphoric acid.
- Phosphate esters represent some of the most important biological compounds.

Key Terms and Concepts

Carboxylate ion (15.3)
Carboxyl group (Introduction)
Carboxylic acid (Introduction)
Carboxylic acid anhydride (15.5)
Carboxylic acid chloride (15.5)
Carboxylic ester (15.5)
Condensation polymerization (15.5)
Dimer (15.2)
Ester (15.8)
Esterification (15.5)
Ester linkage (15.5)
Fatty acid (15.1)
Phosphoric anhydride (15.8)
Saponification (15.7)

Key Equations

1. Dissociation of a carboxylic acid to give a carboxylate ion (**Section 15.3**):	 $R-\overset{O}{\overset{\Vert}{C}}-O-H + H_2O \rightleftharpoons R-\overset{O}{\overset{\Vert}{C}}-O^- + H_3O^+$	Reaction 15.1
2. Reaction of a carboxylic acid with base to produce a carboxylate salt plus water (**Section 15.3**):	 $R-\overset{O}{\overset{\Vert}{C}}-O-H + NaOH \longrightarrow R-\overset{O}{\overset{\Vert}{C}}-O^-Na^+ + H_2O$	Reaction 15.4
3. Reaction of a carboxylic acid with an alcohol to produce an ester plus water (**Section 15.5**):	 $R-\overset{O}{\overset{\Vert}{C}}-OH + H-O-R' \overset{H^+,\ heat}{\rightleftharpoons} R-\overset{O}{\overset{\Vert}{C}}-O-R' + H_2O$	Reaction 15.8

4. Reaction of a carboxylic acid chloride with an alcohol to produce an ester plus hydrogen chloride (**Section 15.5**):	Reaction 15.12  $\mathrm{R-\overset{O}{\overset{\parallel}{C}}-Cl + HO-R' \longrightarrow R-\overset{O}{\overset{\parallel}{C}}-O-R' + HCl}$
5. Reaction of a carboxylic acid anhydride with an alcohol to produce an ester plus a carboxylic acid (**Section 15.5**):	Reaction 15.13  $\mathrm{R-\overset{O}{\overset{\parallel}{C}}-O-\overset{O}{\overset{\parallel}{C}}-R + HO-R' \longrightarrow R-\overset{O}{\overset{\parallel}{C}}-O-R' + R-\overset{O}{\overset{\parallel}{C}}-OH}$
6. Ester hydrolysis to produce a carboxylic acid and alcohol (**Section 15.7**):	Reaction 15.16  $\mathrm{R-\overset{O}{\overset{\parallel}{C}}-OR' + H-OH \overset{H^+}{\rightleftharpoons} R-\overset{O}{\overset{\parallel}{C}}-OH + R'-OH}$
7. Ester saponification to give a carboxylate salt and alcohol (**Section 15.7**):	Reaction 15.18  $\mathrm{R-\overset{O}{\overset{\parallel}{C}}-O-R' + NaOH \longrightarrow R-\overset{O}{\overset{\parallel}{C}}-O^-Na^+ + R'-OH}$
8. Phosphate ester formation (**Section 15.8**):	Reaction 15.20  $\mathrm{R-OH + HO-\underset{\underset{OH}{\vert}}{\overset{\overset{O}{\parallel}}{P}}-OH \rightleftharpoons R-O-\underset{\underset{OH}{\vert}}{\overset{\overset{O}{\parallel}}{P}}-OH + H_2O}$

Exercises

Even-numbered exercises are answered in Appendix B.

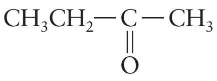
Exercises with an asterisk (*) are more challenging.

The Nomenclature of Carboxylic Acids (Section 15.1)

15.1 What is the structure of the carboxylic acid functional group? How does it differ from the structure of an alcohol and from that of an aldehyde or a ketone?

15.2 Which of the following structures contains a carboxyl group?

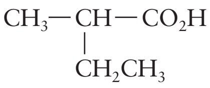
a.



$\mathrm{CH_3CH_2-\underset{\underset{O}{\parallel}}{C}-CH_3}$

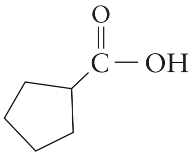
b. $\mathrm{CH_3-CH_2-COOH}$

c.



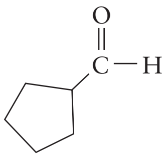
$\mathrm{CH_3-\underset{\underset{CH_2CH_3}{\vert}}{CH}-CO_2H}$

d.

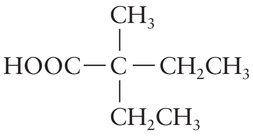


15.3 Which of the following structures contains a carboxyl group?

a.

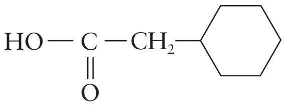


b.



$\mathrm{HOOC-\underset{\underset{CH_2CH_3}{\vert}}{\overset{\overset{CH_3}{\vert}}{C}}-CH_2CH_3}$

c.



d. $\mathrm{CH_3-CO_2H}$

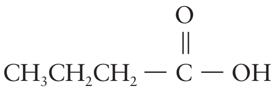
15.4 What structural features are characteristic of fatty acids? Why are fatty acids given that name?

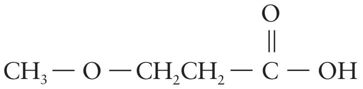
15.5 What compound is responsible for the sour or tart taste of Italian salad dressing (vinegar and oil)?

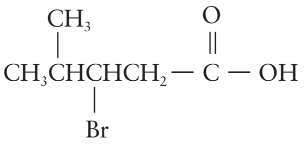
15.6 What carboxylic acid is present in sour milk and sauerkraut?

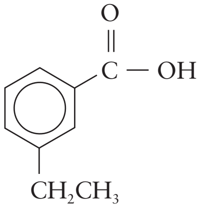
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

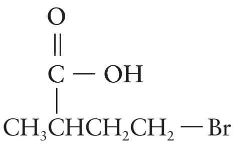
15.7 Write the correct IUPAC name for each of the following:

a. 
$CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-OH$

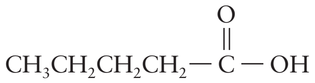
b. 
$CH_3-O-CH_2CH_2-\overset{\overset{O}{\|}}{C}-OH$

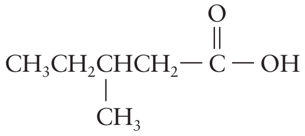
c. 
$CH_3\overset{\overset{CH_3}{|}}{C}H\underset{\underset{Br}{|}}{C}HCH_2-\overset{\overset{O}{\|}}{C}-OH$

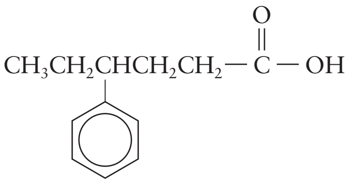
d. 

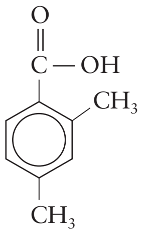
e. 
$CH_3\overset{\overset{\overset{\overset{O}{\|}}{C-OH}}{|}}{C}HCH_2CH_2-Br$

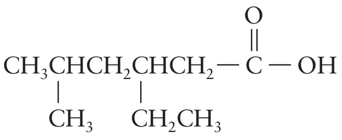
15.8 Write the correct IUPAC name for each of the following:

a. 
$CH_3CH_2CH_2CH_2-\overset{\overset{O}{\|}}{C}-OH$

b. 
$CH_3CH_2\underset{\underset{CH_3}{|}}{C}HCH_2-\overset{\overset{O}{\|}}{C}-OH$

c. 

d. 

e. 
$CH_3\underset{\underset{CH_3}{|}}{C}HCH_2\underset{\underset{CH_2CH_3}{|}}{C}HCH_2-\overset{\overset{O}{\|}}{C}-OH$

15.9 Write a structural formula for each of the following:

- **a.** hexanoic acid
- **b.** 4-bromo-3-methylpentanoic acid
- **c.** *o*-ethylbenzoic acid

15.10 Write a structural formula for each of the following:

- **a.** pentanoic acid
- **b.** 2-bromo-3-methylhexanoic acid
- **c.** 4-propylbenzoic acid

Physical Properties of Carboxylic Acids (Section 15.2)

15.11 Of the classes of organic compounds studied so far, which have particularly unpleasant odors?

15.12 Which compound in each of the following pairs would you expect to have the higher boiling point? Explain your answer.

- **a.** acetic acid or 1-propanol
- **b.** propanoic acid or butanone
- **c.** acetic acid or butyric acid

15.13 Which compound in each of the following pairs would you expect to have the higher boiling point? Explain your answer.

- **a.** butanoic acid or 3-penatanol
- **b.** hexane or pentanoic acid
- **c.** 2-pentanone or hexanoic acid

15.14 List the following compounds in order of increasing boiling point:

- **a.** pentanal
- **b.** hexane
- **c.** 1-pentanol
- **d.** butanoic acid

15.15 List the following compounds in order of increasing boiling point:

- **a.** 2-butanone
- **b.** propanoic acid
- **c.** pentane
- **d.** 1-butanol

15.16 Draw the structure of the dimer formed when two molecules of propanoic acid hydrogen bond with each other.

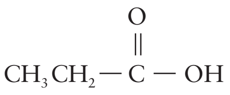
15.17 Use a dotted line to show hydrogen bonding between an acetic acid molecule and

- **a.** another acetic acid molecule
- **b.** water molecules

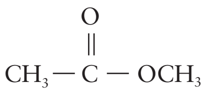
15.18 Use a dotted line to show hydrogen bonding between a propanoic acid molecule and

- **a.** another propanoic acid molecule
- **b.** water molecules

15.19 The two isomers propanoic acid and methyl acetate are both liquids. One boils at 141°C, the other at 57°C.


$CH_3CH_2-\overset{\overset{O}{\|}}{C}-OH$

propanoic acid


$CH_3-\overset{\overset{O}{\|}}{C}-OCH_3$

methyl acetate

- **a.** Predict which compound boils at 57°C and which at 141°C. Explain your reasoning.
- **b.** Which of these two compounds would you predict to be more soluble in water? Explain.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

15.20 Caproic acid, a six-carbon acid, has a solubility in water of 1 g/100 mL of water (**Table 15.2**). Which part of the structure of caproic acid is responsible for its solubility in water, and which part prevents greater solubility?

15.21 Why are acetic acid, sodium acetate, and sodium caprate all soluble in water, whereas capric acid, a 10-carbon fatty acid, is not?

15.22 List the following compounds in order of increasing water solubility:

a. ethoxyethane **c.** pentane
b. propanoic acid **d.** 1-butanol

15.23 List the following compounds in order of increasing water solubility:

a. hexane **c.** 3-pentanone
b. 2-pentanol **d.** pentanoic acid

The Acidity of Carboxylic Acids (Section 15.3)

15.24 Draw the structural formula for the carboxylate ion of propanoic acid.

15.25 Draw the structural formula for the carboxylate ion of 3-phenylpentanoic acid.

15.26 Draw structural formulas for the following carboxylic acids and circle the acidic hydrogen atoms present:

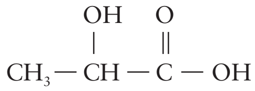
a. 3-bromopropanoic acid
b. butanoic acid
c. 2,3,4-trimethylpentanoic acid

15.27 Draw structural formulas for the following carboxylic acids and circle the acidic hydrogen atoms present:

a. pentanoic acid
b. 3,4-dichlorobutanoic acid
c. 3,3,5-trimethylhexanoic acid

15.28 What is the most important chemical property of carboxylic acids?

15.29 As we discuss the cellular importance of lactic acid in a later chapter, we will refer to this compound as lactate. Explain why.



$$CH_3-\overset{OH}{\overset{|}{CH}}-\overset{O}{\overset{\|}{C}}-OH$$

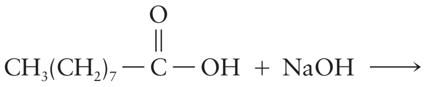
lactic acid

15.30 Write an equation to illustrate the equilibrium that is present when propanoic acid is dissolved in water. What structure predominates when OH^- is added to raise the pH to 12? What structure predominates as acid is added to lower the pH to 2?

15.31 Draw a structural formula that shows which form of butyric acid would predominate at a pH of 2.

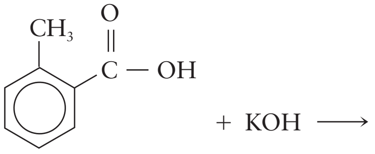
15.32 Complete each of the following reactions:

a.



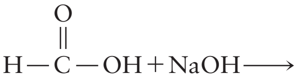
$$CH_3(CH_2)_7-\overset{O}{\overset{\|}{C}}-OH + NaOH \longrightarrow$$

b.



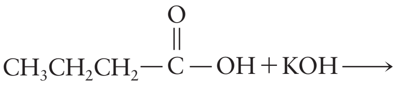
15.33 Complete each of the following reactions:

a.



$$H-\overset{O}{\overset{\|}{C}}-OH+NaOH\longrightarrow$$

b.



$$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-OH+KOH\longrightarrow$$

15.34 Write a balanced equation for the reaction of butanoic acid with each of the following:

a. KOH **b.** H_2O **c.** NaOH

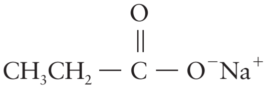
15.35 Write a balanced equation for the reaction of acetic acid with each of the following:

a. NaOH **b.** KOH **c.** $Ca(OH)_2$

Salts of Carboxylic Acids (Section 15.4)

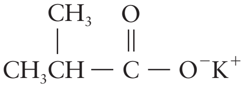
15.36 Give the IUPAC name for each of the following:

a.



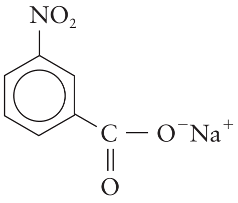
$$CH_3CH_2-\overset{O}{\overset{\|}{C}}-O^-Na^+$$

b.



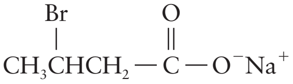
$$\overset{CH_3}{\overset{|}{CH_3CH}}-\overset{O}{\overset{\|}{C}}-O^-K^+$$

c.



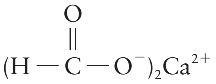
15.37 Give the IUPAC name for each of the following:

a.



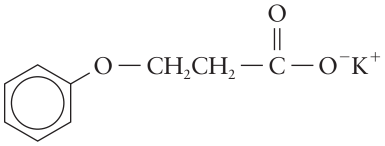
$$CH_3\overset{Br}{\overset{|}{CH}}CH_2-\overset{O}{\overset{\|}{C}}-O^-Na^+$$

b.



$$(H-\overset{O}{\overset{\|}{C}}-O^-)_2Ca^{2+}$$

c.



15.38 Draw structural formulas for the following:

a. sodium formate
b. calcium benzoate
c. sodium 2-methylbutanoate

15.39 Draw structural formulas for the following:

a. potassium ethanoate
b. sodium *m*-methylbenzoate
c. sodium 2-methylbutanoate

15.40 Name each of the following:

a. The sodium salt of valeric acid
b. The magnesium salt of lactic acid
c. The potassium salt of citric acid

15.41 Name each of the following:

a. The potassium salt of acetic acid
b. The sodium salt of benzoic acid
c. The magnesium salt of oxalic acid

15.42 Give the name of a carboxylic acid or carboxylate salt used in each of the following ways:

- **a.** As a soap.
- **b.** As a mold inhibitor used in bread.
- **c.** As a food additive noted for its pH buffering ability.
- **d.** As a preservative used in soft drinks.

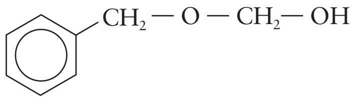
15.43 Give the name of a carboxylic acid or carboxylate salt used in each of the following ways:

- **a.** As a treatment for athlete's foot.
- **b.** As a general food preservative used to pickle vegetables.
- **c.** As a food preservative found naturally in many foods.
- **d.** To maintain the structure of foams and gels.

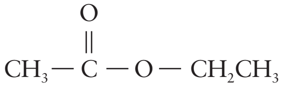
Carboxylic Esters (Section 15.5)

15.44 Which of the following compounds are esters?

a.

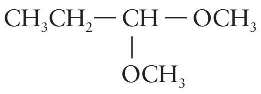


b.



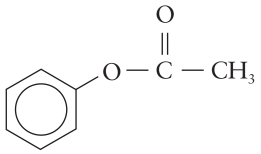
$CH_3-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3$

c.



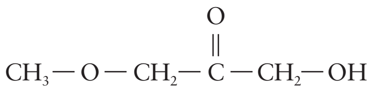
$CH_3CH_2-\underset{\underset{OCH_3}{|}}{CH}-OCH_3$

d.



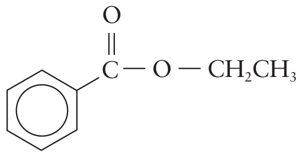
15.45 Which of the following compounds are esters?

a.



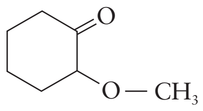
$CH_3-O-CH_2-\overset{O}{\overset{\|}{C}}-CH_2-OH$

b.



c. CH_3-O-CH_3

d.



15.46 For each ester in Exercise 15.44, draw a circle around the portion that came from the acid and use an arrow to point out the *ester linkage.*

15.47 For each ester in Exercise 15.45, draw a circle around the portion that came from the acid and use an arrow to point out the ester linkage.

15.48 Draw the structural formula of the ester made when each of the following carboxylic acids and alcohols react:

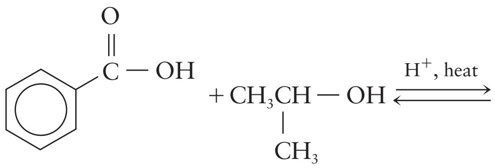
- **a.** methanoic acid and methanol
- **b.** propanoic acid and ethanol
- **c.** 2-methylpropanoic acid and 2-butanol
- **d.** butanoic acid and 2-propanol

15.49 Draw the structural formula of the ester made when each of the following carboxylic acids and alcohols react:

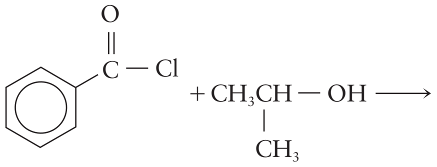
- **a.** propanoic acid and 2-propanol
- **b.** ethanoic acid and 1-propanol
- **c.** 2-methylbutanoic acid and ethanol
- **d.** methanoic acid and 2-butanol

15.50 Complete the following reactions:

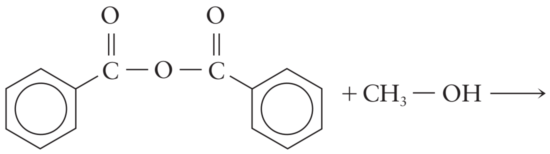
a.



b.

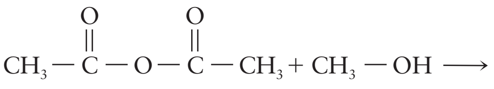


c.



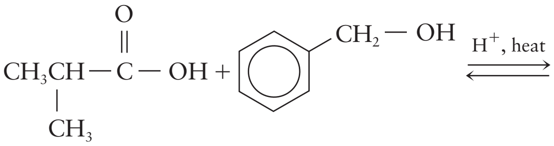
15.51 Complete the following reactions:

a.

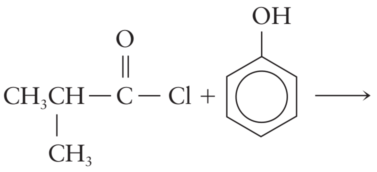


$CH_3-\overset{O}{\overset{\|}{C}}-O-\overset{O}{\overset{\|}{C}}-CH_3 + CH_3-OH \longrightarrow$

b.

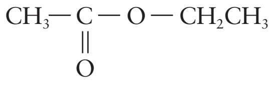


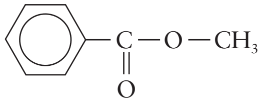
c.

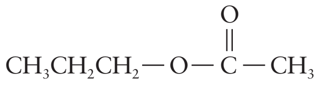


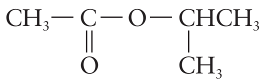
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

15.52 Draw the structural formulas of the "parent" carboxylic acid and the "parent" alcohol reacted to make each of the following esters:

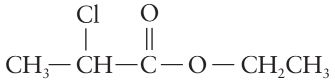
a. 
$CH_3-\underset{\underset{O}{\|}}{C}-O-CH_2CH_3$

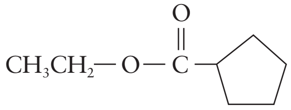
b. 

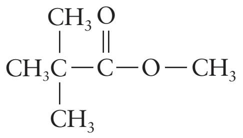
c. 
$CH_3CH_2CH_2-O-\overset{\overset{O}{\|}}{C}-CH_3$

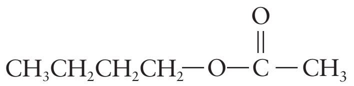
d. 
$CH_3-\underset{\underset{O}{\|}}{C}-O-\underset{\underset{CH_3}{|}}{C}HCH_3$

15.53 Draw the structural formulas of the "parent" carboxylic acid and the "parent" alcohol reacted to make each of the following esters:

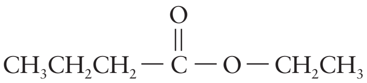
a. 
$CH_3-\overset{\overset{Cl}{|}}{CH}-\overset{\overset{O}{\|}}{C}-O-CH_2CH_3$

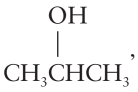
b. 

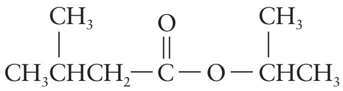
c. 
$CH_3\overset{\overset{CH_3}{|}}{\underset{\underset{CH_3}{|}}{C}}-\overset{\overset{O}{\|}}{C}-O-CH_3$

d. 
$CH_3CH_2CH_2CH_2-O-\overset{\overset{O}{\|}}{C}-CH_3$

15.54 Using the alcohol CH_3CH_2—OH, show three different starting compounds that may be used to synthesize the ester:


$CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-O-CH_2CH_3$

15.55 Using the alcohol  $CH_3\overset{\overset{OH}{|}}{C}HCH_3$, show three different starting compounds that may be used to synthesize the ester:


$CH_3\overset{\overset{CH_3}{|}}{C}HCH_2-\overset{\overset{O}{\|}}{C}-O-\overset{\overset{CH_3}{|}}{C}HCH_3$

15.56 Give the structures of the ester that forms when propanoic acid is reacted with the following:

a. methyl alcohol

b. phenol

c. 2-methyl-1-propanol

15.57 Give the structures of the ester that forms when butanoic acid is reacted with the following:

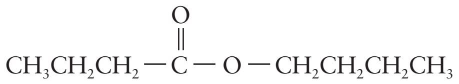
a. propanol

b. 3-methylcyclopentanol

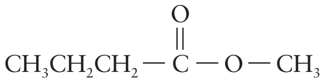
c. 3-chloro-2-butanol

15.58 The structures of two esters used as artificial flavorings are given below. Write the structure of the acid and the alcohol from which each ester could be synthesized.

a. Pineapple flavoring,

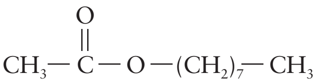

$CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-O-CH_2CH_2CH_2CH_3$

b. Apple flavoring,

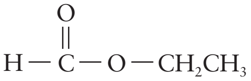

$CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-O-CH_3$

15.59 The structures of two esters used as artificial flavorings are given below. Write the structure of the acid and the alcohol from which each ester could be synthesized.

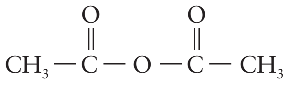
a. Orange flavoring.


$CH_3-\overset{\overset{O}{\|}}{C}-O-(CH_2)_7-CH_3$

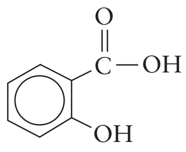
b. Raspberry flavoring.


$H-\overset{\overset{O}{\|}}{C}-O-CH_2CH_3$

15.60 Aspirin is formed by reacting salicylic acid with 1 mol of acetic anhydride to form the ester. Show the structure of aspirin.


$CH_3-\overset{\overset{O}{\|}}{C}-O-\overset{\overset{O}{\|}}{C}-CH_3$

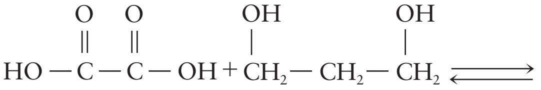
acetic anhydride



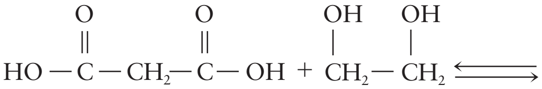
salicylic acid

15.61 How do the acids and alcohols involved in polyester formation differ from those that commonly form simple esters?

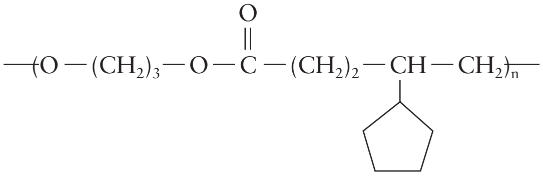
15.62 Draw the structure of the repeating monomer unit in the polyester formed in the condensation of oxalic acid and 1,3-propanediol.


$HO-\overset{\overset{O}{\|}}{C}-\overset{\overset{O}{\|}}{C}-OH+\overset{\overset{OH}{|}}{CH_2}-CH_2-\overset{\overset{OH}{|}}{CH_2} \rightleftarrows$

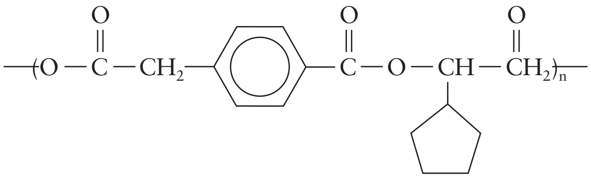
15.63 Draw the structure of the repeating monomer unit in the polyester formed in the condensation of malonic acid and ethylene glycol.


$HO-\overset{\overset{O}{\|}}{C}-CH_2-\overset{\overset{O}{\|}}{C}-OH+\overset{\overset{OH}{|}}{CH_2}-\overset{\overset{OH}{|}}{CH_2} \rightleftarrows$

15.64 Draw the structural formula of the monomer needed to make the following polyester:



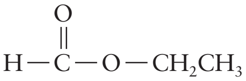
15.65 Draw the structural formula of the monomers needed to make the following polyester:



The Nomenclature of Esters (Section 15.6)

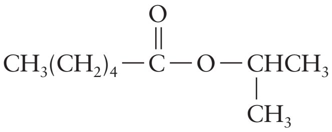
15.66 Assign common names to the following esters. Refer to **Table 15.1** for the common names of the acids.

a.



$$H-\overset{\overset{O}{\|}}{C}-O-CH_2CH_3$$

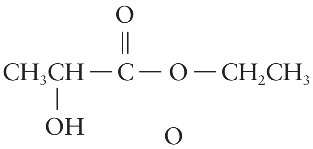
b.



$$CH_3(CH_2)_4-\overset{\overset{O}{\|}}{C}-O-\underset{\underset{CH_3}{|}}{CHCH_3}$$

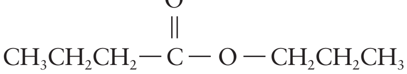
15.67 Assign common names to the following esters. Refer to **Table 15.1** for the common names of the acids.

a.



$$CH_3\underset{\underset{OH}{|}}{CH}-\overset{\overset{O}{\|}}{C}-O-CH_2CH_3$$

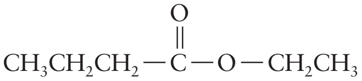
b.



$$CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-O-CH_2CH_2CH_3$$

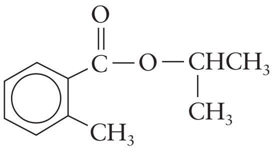
15.68 Give the IUPAC name for each of the following:

a.



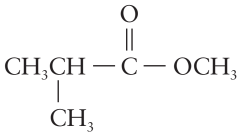
$$CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-O-CH_2CH_3$$

b.



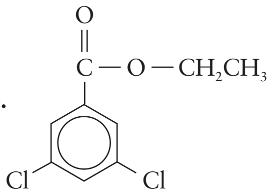
15.69 Give the IUPAC name for each of the following:

a.



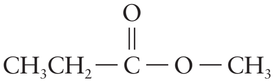
$$CH_3\underset{\underset{CH_3}{|}}{CH}-\overset{\overset{O}{\|}}{C}-OCH_3$$

b.



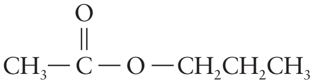
15.70 Assign common names to the following esters. Refer to **Table 15.1** for the common names of the acids.

a.



$$CH_3CH_2-\overset{\overset{O}{\|}}{C}-O-CH_3$$

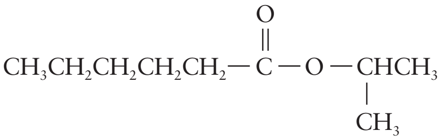
b.



$$CH_3-\overset{\overset{O}{\|}}{C}-O-CH_2CH_2CH_3$$

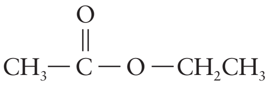
15.71 Assign common names to the following esters. Refer to **Table 15.1** for the common names of the acids.

a.



$$CH_3CH_2CH_2CH_2CH_2-\overset{\overset{O}{\|}}{C}-O-\underset{\underset{CH_3}{|}}{CHCH_3}$$

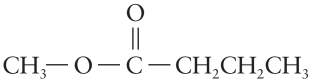
b.



$$CH_3-\overset{\overset{O}{\|}}{C}-O-CH_2CH_3$$

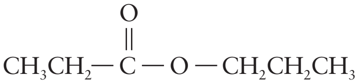
15.72 Give the IUPAC name for each of the following:

a.



$$CH_3-O-\overset{\overset{O}{\|}}{C}-CH_2CH_2CH_3$$

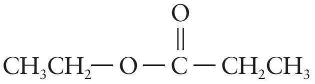
b.



$$CH_3CH_2-\overset{\overset{O}{\|}}{C}-O-CH_2CH_2CH_3$$

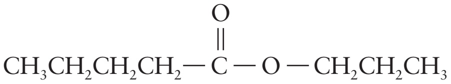
15.73 Give the IUPAC name for each of the following:

a.



$$CH_3CH_2-O-\overset{\overset{O}{\|}}{C}-CH_2CH_3$$

b.



$$CH_3CH_2CH_2CH_2-\overset{\overset{O}{\|}}{C}-O-CH_2CH_2CH_3$$

15.74 Assign IUPAC names to the simple esters produced by a reaction between ethanoic acid and the following:

a. ethanol **b.** 1-propanol **c.** 1-butanol

15.75 Assign IUPAC names to the esters produced by a reaction between butanoic acid and the following:

a. 1-butanol

b. Methanol

c. 1-propanol

15.76 Assign common names to the simple esters produced by a reaction between methanol and the following:

a. propionic acid **b.** butyric acid **c.** lactic acid

15.77 Assign common names to the esters produced by a reaction between 1-propanol and the following:

a. acetic acid

b. butyric acid

c. formic acid

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

15.78 Draw structural formulas for the following:

- **a.** methyl ethanoate
- **b.** propyl 2-bromobenzoate
- **c.** ethyl 3,4-dimethylpentanoate

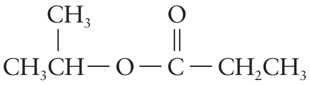
15.79 Draw structural formulas for the following:

- **a.** phenyl formate
- **b.** methyl 4-nitrobenzoate
- **c.** ethyl 2-chloropropanoate

Reactions of Esters (Section 15.7)

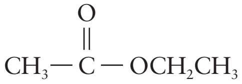
15.80 Define and compare the terms *ester hydrolysis* and *saponification.*

15.81 Write equations for the hydrolysis and saponification of isopropyl propionate:



$$\underset{}{\overset{\displaystyle CH_3}{\overset{|}{CH_3CH}}}-O-\overset{\displaystyle O}{\overset{\|}{C}}-CH_2CH_3$$

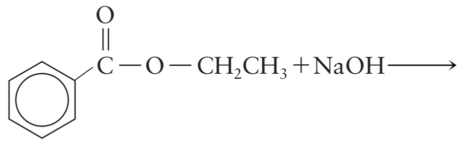
15.82 Write equations for the hydrolysis and saponification of ethyl acetate:



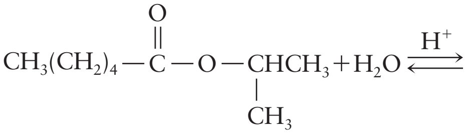
$$CH_3-\overset{\displaystyle O}{\overset{\|}{C}}-OCH_2CH_3$$

15.83 Complete the following reactions:

a.



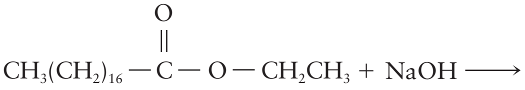
b.



$$CH_3(CH_2)_4-\overset{\displaystyle O}{\overset{\|}{C}}-O-\underset{\underset{\displaystyle CH_3}{|}}{CHCH_3}+H_2O \xrightleftharpoons{H^+}$$

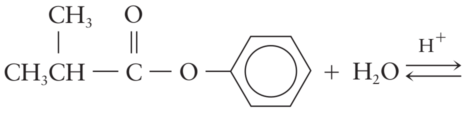
15.84 Complete the following reactions:

a.



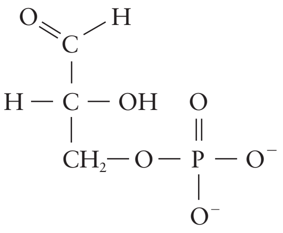
$$CH_3(CH_2)_{16}-\overset{\displaystyle O}{\overset{\|}{C}}-O-CH_2CH_3 + NaOH \longrightarrow$$

b.



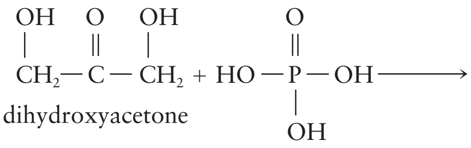
Esters of Inorganic Acids (Section 15.8)

15.85 Glyceraldehyde-3-phosphate, an important compound in the cellular oxidation of carbohydrates, is an ester of phosphoric acid and glyceraldehyde.



- **a.** Give the structure of glyceraldehyde.
- **b.** Why is glyceraldehyde-3-phosphate shown with a 2^- charge?

15.86 Dihydroxyacetone reacts with phosphoric acid to form the monoester called dihydroxyacetone phosphate. Complete the reaction for its formation.



$$\overset{\displaystyle OH}{\overset{|}{CH_2}}-\overset{\displaystyle O}{\overset{\|}{C}}-\overset{\displaystyle OH}{\overset{|}{CH_2}} + HO-\underset{\underset{\displaystyle OH}{|}}{\overset{\displaystyle O}{\overset{\|}{P}}}-OH \longrightarrow$$

dihydroxyacetone

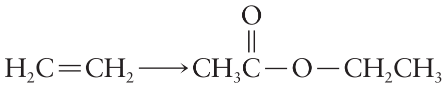
15.87 Give the structure for the following:

- **a.** monoethyl phosphate (with a 2^- charge)
- **b.** monoethyl diphosphate (with a 3^- charge)
- **c.** monoethyl triphosphate (with a 4^- charge)

Additional Exercises

15.88 Explain how a sodium bicarbonate ($NaHCO_3$) solution can be used to distinguish between a carboxylic acid solution and an alcohol solution.

15.89 The following reaction requires several steps. Show the reagents you would use and draw structural formulas for intermediate compounds formed in each step.

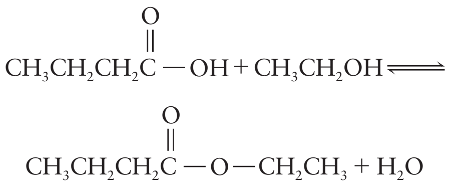


$$H_2C=CH_2 \longrightarrow CH_3\overset{\displaystyle O}{\overset{\|}{C}}-O-CH_2CH_3$$

15.90 Draw the structural formula and give the IUPAC name for the ester that results when 3-Ethylhexanoic acid reacts with phenol.

15.91 How many mL of a 0.100 M NaOH solution would be needed to titrate 0.156 g of butanoic acid to a neutral pH endpoint?

15.92 Identify two things that can be done to the following equilibrium to achieve 100% conversion of butanoic acid to ethyl butanoate.



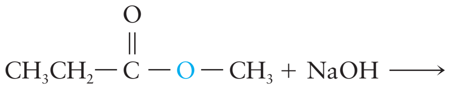
$$CH_3CH_2CH_2\overset{\displaystyle O}{\overset{\|}{C}}-OH+CH_3CH_2OH \rightleftharpoons CH_3CH_2CH_2\overset{\displaystyle O}{\overset{\|}{C}}-O-CH_2CH_3+H_2O$$

Chemistry for Thought

15.93 Citric acid is often added to carbonated beverages as a flavoring. Why is citric acid viewed as a “safe” food additive?

15.94 Ester formation (Reaction 15.8) and ester hydrolysis (Reaction 15.16) are exactly the same reaction, only written in reverse. What determines which direction the reaction proceeds and what actually forms?

15.95 Write a mechanism for the following reaction. Show the final location of the oxygen atom in the second color.



$$CH_3CH_2-\overset{\displaystyle O}{\overset{\|}{C}}-O-CH_3 + NaOH \longrightarrow$$

15.96 Answer the question in **Figure 15.1**. What flavor sensation is characteristic of acids?

15.97 Oxalic acid, the substance mentioned in **Figure 15.2**, has two carboxyl groups. If you were to give this compound an IUPAC name, what ending would be appropriate?

15.98 Why is it safe for us to consume foods like vinegar that contain acetic acids?

15.99 A Dacron patch is sometimes used in heart surgery. Why do polyesters like the Dacron patch resist hydrolysis reactions that would result in deterioration of the patch?

15.100 Citrus fruits such as grapefruit and oranges may be kept for several weeks without refrigeration. Offer some possible reasons why the spoilage rate is not higher.

15.101 In **Section 18.3**, locate the structure of a triglyceride. Draw its structure and circle the ester linkages.

15.102 **Section 21.2** shows a tetranucleotide structure. Draw a portion of the structure and circle the portion representing the phosphate diester.

16 Amines and Amides

NESE ELM 2
N JUNIPER 2
CAT HAIR 2

Julien McRoberts/Adobe Stock Photos

Health Career Focus

ALLERGY/IMMUNOLOGY NURSE

My son suffered from severe allergies. He'd rub his eyes until they swelled shut. After his allergy test, the doctor said he reacted to every grass, tree, and animal on the skin test. On a scale of 1 to 8, most of his reactions approached 8. Since antihistamines offered little relief, biweekly allergy shots were recommended.

The shot is quick, but there's a 15-minute wait afterward to make sure there isn't a reaction to the unique mixture of allergens prepared for each patient. It's important to keep your shot appointments—if you miss a week or two, the dosage can't be increased and there's no progress toward developing resistance to the allergens.

An allergy nurse inspects the injection site and records the result. If the red spot from the shot stays within limits, they can increase the dosage next time. If the reaction is too large, they back off on the strength, or tell you to wait another week.

Allergy shots made such a difference in my son's life!

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Given structural formulas, classify amines as primary, secondary, or tertiary. **(Section 16.1)**
2. Assign common and IUPAC names to simple amines. **(Section 16.2)**
3. Discuss how hydrogen bonding influences the physical properties of amines. **(Section 16.3)**
4. Recognize and write key reactions for amines. **(Section 16.4)**
5. Name amines used as neurotransmitters. **(Section 16.5)**
6. Give uses for specific biological amines. **(Section 16.6)**
7. Assign IUPAC names for amides. **(Section 16.7)**
8. Show the formation of hydrogen bonds with amides. **(Section 16.8)**
9. Give the products of acidic and basic hydrolysis of amides. **(Section 16.9)**

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

THE EFFECTIVENESS of a wide variety of important medicines depends either entirely or partly on the presence of a nitrogen-containing group in their molecules. Nitrogen-containing functional groups are found in more medications than any other type of functional group. In this chapter, we will study two important classes of organic nitrogen compounds, the amines and the amides.

Both amines and amides are abundant in nature, where they play important roles in the chemistry of life. Our study of these two functional classes will help prepare us for later chapters dealing with amino acids, proteins, and nucleic acids, and provide a basis for understanding the structures and chemistry of a number of medicines.

16.1 Classification of Amines

Learning Objective 1 Classify amines as primary, secondary, or tertiary on the basis of given structural formulas.

Amines are organic derivatives of ammonia, NH_3, in which one or more of the hydrogens are replaced by an aromatic or alkyl group (R). Like alcohols, amines are classified as primary, secondary, or tertiary on the basis of molecular structure. However, the classification is done differently. When classifying amines, the number of groups (R) that have replaced hydrogens in the NH_3 is counted. The nitrogen atom in a **primary amine** is bonded to one R group. The nitrogen in **secondary amines** is bonded to two R groups, and that of **tertiary amines** is bonded to three R groups. These amine subclasses are summarized in **Table 16.1**.

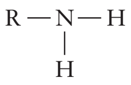
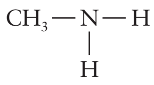
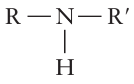
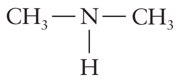
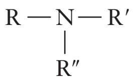
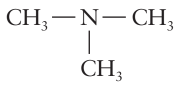
amine An organic compound derived by replacing one or more of the hydrogen atoms of ammonia with alkyl or aromatic groups, as in RNH_2, R_2NH, and R_3N.

primary amine An amine having one alkyl or aromatic group bonded to nitrogen, as in R—NH_2.

secondary amine An amine having two alkyl or aromatic groups bonded to nitrogen, as in R_2NH.

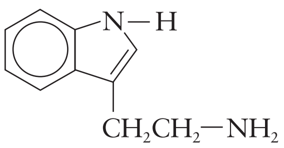
tertiary amine An amine having three alkyl or aromatic groups bonded to nitrogen, as in R_3N.

TABLE 16.1 Subclasses of Amines

Subclass	General Formula	Example
Primary (1°)	 $R-\underset{H}{\underset{\mid}{N}}-H$	 $CH_3-\underset{H}{\underset{\mid}{N}}-H$
Secondary (2°)	 $R-\underset{H}{\underset{\mid}{N}}-R'$	 $CH_3-\underset{H}{\underset{\mid}{N}}-CH_3$
Tertiary (3°)	 $R-\underset{R''}{\underset{\mid}{N}}-R'$	 $CH_3-\underset{CH_3}{\underset{\mid}{N}}-CH_3$

Example 16.1 Classifying Amines

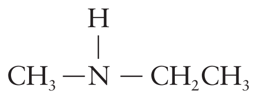
Serotonin, an amine involved in the transmission of nerve impulses, contains two nitrogen atoms in its structure. Classify each of the following nitrogens as primary, secondary, or tertiary.



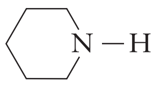
Solution

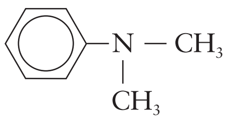
The ring nitrogen is bonded to two carbon atoms, making it secondary. The NH_2 nitrogen atom is bonded to one carbon atom, so it is primary.

✔ **LEARNING CHECK 16.1** Classify each of the following amines as primary, secondary, or tertiary:

a. 

$$CH_3-\overset{\overset{\displaystyle H}{|}}{N}-CH_2CH_3$$

b. 

c. 

16.2 The Nomenclature of Amines

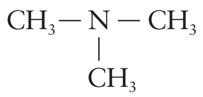
Learning Objective 2 Assign common and IUPAC names to simple amines.

Several approaches are used in naming amines. Common names are used extensively for those with low molecular weights. These are named by alphabetically linking the names of the alkyl or aromatic groups bonded to the nitrogen and attaching the suffix *-amine.* The name is written as one word, and the prefixes *di-* and *tri-* are used when identical alkyl groups are present. Some examples are

$CH_3—NH_2$	$CH_3—NH—CH_3$	$CH_3CH_2—NH—CH_3$
methylamine	dimethylamine	ethylmethylamine

Example 16.2 Naming Amines

The nitrogen compound with three attached methyl groups is a gas with a strong fishy odor, used as a warning (smell) agent in natural gas. Assign a common name to this amine.



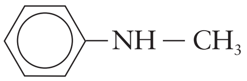
$$CH_3-\underset{\underset{\displaystyle CH_3}{|}}{N}-CH_3$$

Solution

With three identical groups attached to nitrogen, the prefix *tri-* can be used. The name is trimethylamine.

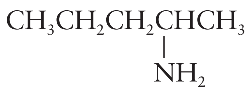
✔ **LEARNING CHECK 16.2** Assign a common name to the following amines:

a. $CH_3CH_2CH_2—NH_2$

b. 

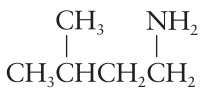
c. $CH_3CH_2CH_2—NH—CH_2CH_3$

An IUPAC approach for naming amines is similar to that for alcohols. The root name is determined by the longest continuous chain of carbon atoms. The *-e* ending in the alkane name is changed to *–amine*. The position of the amino group on the chain is shown by a number. Numbers are also used to locate other substituents on the carbon chain. An italic capital *N* is used as a prefix for a substituent on nitrogen.



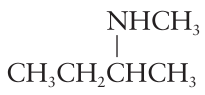
$$CH_3CH_2CH_2\underset{\underset{\displaystyle NH_2}{|}}{CH}CH_3$$

2-pentanamine



$$CH_3\overset{\overset{\displaystyle CH_3}{|}}{C}HCH_2\overset{\overset{\displaystyle NH_2}{|}}{CH_2}$$

3-methyl-1-butanamine

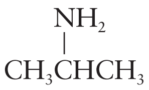


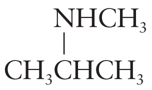
$$CH_3CH_2\overset{\overset{\displaystyle NHCH_3}{|}}{C}HCH_3$$

N-methyl-2-butanamine

Example 16.3 More Naming Amines

Give an IUPAC name for the following amines:

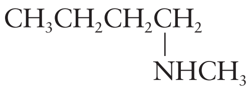
a. 
$CH_3\overset{NH_2}{\overset{|}{C}}HCH_3$

b. 
$CH_3\overset{NHCH_3}{\overset{|}{C}}HCH_3$

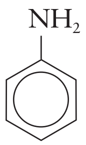
Solution

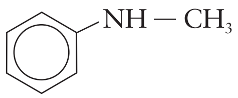
a. The carbon chain is three atoms in length, so the base word is propane. At position 2, there is an amino group: the name is 2-propanamine.
b. A methyl group is attached to the nitrogen. The IUPAC name is *N*-methyl-2-propanamine.

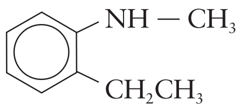
✔ LEARNING CHECK 16.3 Give an IUPAC name for the following amines:

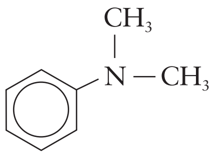
a. $CH_3CH_2CH_2CH_2-NH_2$ b. 
$CH_3CH_2CH_2\underset{NHCH_3}{\underset{|}{CH_2}}$

Aromatic amines are usually given names (both common and IUPAC) based on aniline, the simplest aromatic amine. They are named as substituted anilines, and an italic capital *N* is used to indicate that an alkyl group is attached to the nitrogen and not to the ring. If two groups are attached to the nitrogen, an italic capital *N* is used for each one. Some examples are


aniline

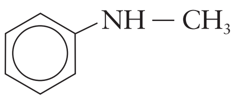

N-methylaniline

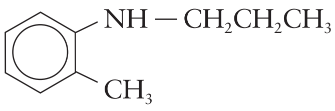

2-ethyl-*N*-methylaniline


N,*N*-dimethylaniline

Example 16.4 Naming Anilines

Aniline is used to make a wide variety of products, such as polyurethane foam, synthetic dyes, herbicides, and varnishes. Name the following amines as derivatives of aniline:

a. 

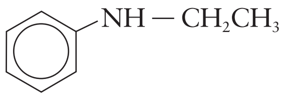
b. 

Solution

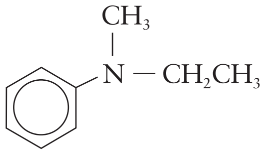
a. *N*-methylaniline
b. 2-methyl-*N*-propylaniline

✔ **LEARNING CHECK 16.4** Name the following amines as derivatives of aniline:

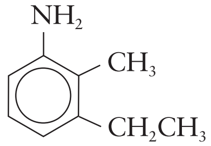
a.



b.



c.

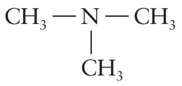
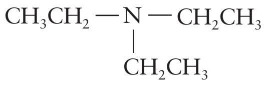


16.3 Physical Properties of Amines

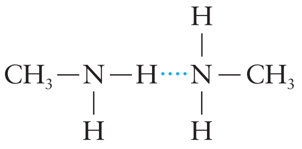
Learning Objective 3 Discuss how hydrogen bonding influences the physical properties of amines.

The simple, low-molecular-weight amines are gases at room temperature (see **Table 16.2**). Heavier, more complex compounds are liquids or solids.

TABLE 16.2 Properties of Some Amines

Name	Structure	Melting Point (°C)	Boiling Point (°C)
Methylamine	CH_3-NH_2	−94	−6
Ethylamine	$CH_3CH_2-NH_2$	−81	17
Dimethylamine	$CH_3-NH-CH_3$	−93	7
Diethylamine	$CH_3CH_2-NH-CH_2CH_3$	−48	56
Trimethylamine	 $CH_3-\underset{\displaystyle CH_3}{\underset{\vert}{N}}-CH_3$	−117	3
Triethylamine	 $CH_3CH_2-\underset{\displaystyle CH_2CH_3}{\underset{\vert}{N}}-CH_2CH_3$	−114	89

Like alcohols, primary and secondary amines form hydrogen bonds among themselves:



$$CH_3-\underset{\displaystyle H}{\underset{\vert}{N}}-H\cdots\overset{\displaystyle H}{\overset{\vert}{\underset{\displaystyle H}{\underset{\vert}{N}}}}-CH_3$$

Because nitrogen is less electronegative than oxygen, the hydrogen bonds formed by amines are weaker than those formed by alcohols. For this reason, the boiling points of primary and secondary amines are usually somewhat lower than the boiling points of alcohols with similar molecular weights. Tertiary amines cannot form hydrogen bonds among themselves (because the nitrogen has no attached hydrogen atom), and their boiling points are similar to those of alkanes that have about the same molecular weights.

Amines with fewer than six carbon atoms are generally soluble in water as a result of hydrogen bond formation between amine functional groups and water molecules. This is true for tertiary as well as primary and secondary amines (see **Figure 16.1**).

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

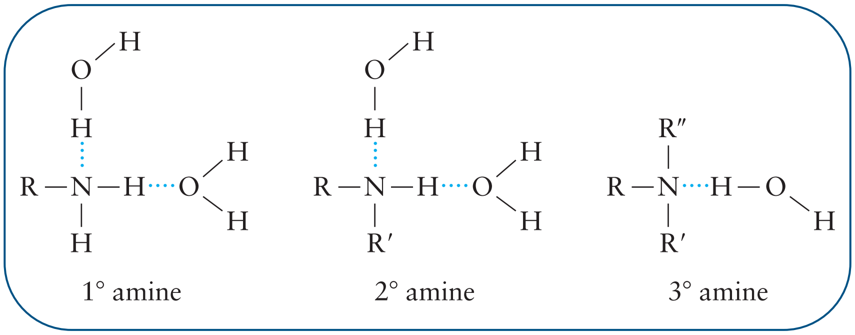


FIGURE 16.1 Hydrogen bonding between amines in water.

Low-molecular-weight amines have a sharp, penetrating odor similar to that of ammonia. Somewhat larger amines have an unpleasant odor reminiscent of decaying fish (see **Figure 16.2**). In fact, some amines are partially responsible for the odor of decaying animal tissue. Two such compounds have especially descriptive common names—putrescine and cadaverine:

$H_2N—CH_2CH_2CH_2CH_2—NH_2$
putrescine
(1,4-diaminobutane)

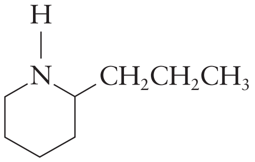
$H_2N—CH_2CH_2CH_2CH_2CH_2—NH_2$
cadaverine
(1,5-diaminopentane)

Denis Val/Shutterstock.com

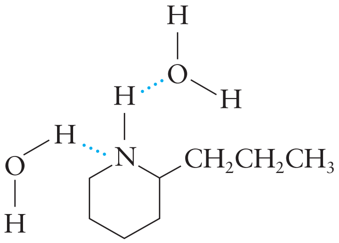
FIGURE 16.2 The fishy odor caused by the presence of amines can be reduced by the reaction of organic acids in lemon juice.

Example 16.5 Showing Hydrogen Bonding

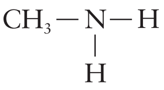
Coniine is a cyclic amine giving rise to the toxicity of poison hemlock. Draw structural formulas to show how coniine can form hydrogen bonds with water.

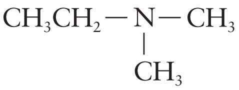


Solution



✔ LEARNING CHECK 16.5 Draw structural formulas to show how each of the following amines forms hydrogen bonds with water:

a. 
$CH_3-\underset{\underset{\displaystyle H}{|}}{N}-H$

b. 
$CH_3CH_2-\underset{\underset{\displaystyle CH_3}{|}}{N}-CH_3$

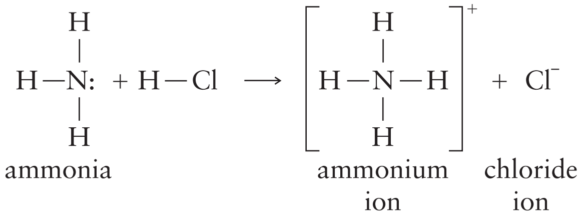
16.4 Chemical Properties of Amines

Learning Objective 4 Recognize and write key reactions for amines.

Amines undergo many chemical reactions, but we will limit our study to the two most important properties of amines: basicity and amide formation.

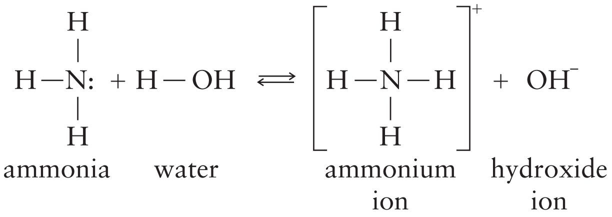
16.4A Basicity and Amine Salts

The single most distinguishing feature of amines is their behavior as weak bases. They are the most common organic bases. We know from inorganic chemistry that ammonia behaves as a Brønsted base by accepting protons, and in the process becomes a conjugate acid. The reaction of NH_3 with HCl gas illustrates this point (Reaction 16.1):



$$\underset{\text{ammonia}}{H-\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{N}}}}:} + H-Cl \longrightarrow \underset{\text{ammonium ion}}{\left[H-\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{N}}}}-H\right]^+} + \underset{\text{chloride ion}}{Cl^-} \qquad (16.1)$$

We also remember from inorganic chemistry that Brønsted bases such as ammonia react with water to liberate OH^- ions (Reaction 16.2):



$$\underset{\text{ammonia}}{H-\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{N}}}}:} + \underset{\text{water}}{H-OH} \rightleftarrows \underset{\text{ammonium ion}}{\left[H-\overset{\displaystyle H}{\underset{\displaystyle H}{\overset{|}{\underset{|}{N}}}}-H\right]^+} + \underset{\text{hydroxide ion}}{OH^-} \qquad (16.2)$$

Because the amines are derivatives of ammonia, they react in similar ways. In water, they produce OH^- ions:

General reaction: $R—NH_2 + H_2O \rightleftarrows R—NH_3^+ + OH^-$ (16.3)

Specific reaction: $\underset{\text{methylamine}}{CH_3—NH_2} + H_2O \rightleftarrows \underset{\text{methylammonium ion}}{CH_3—NH_3^+} + OH^-$ (16.4)

Example 16.6 Completing Reactions

Complete the following reaction:

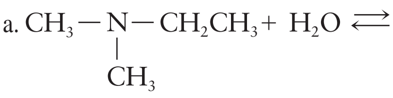
$$CH_3—NH—CH_3 + H_2O \rightleftarrows$$

Solution

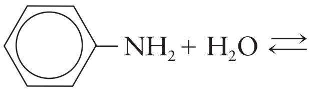
Primary, secondary, and tertiary amines are all basic and exhibit the same reaction in water.

$$CH_3—NH—CH_3 + H_2O \rightleftarrows CH_3—\overset{+}{N}H_2—CH_3 + OH^-$$

✔ **LEARNING CHECK 16.6** Complete the following reactions:

a. 

$$CH_3-\underset{\displaystyle CH_3}{\underset{|}{N}}-CH_2CH_3 + H_2O \rightleftarrows$$

b. 

$$-NH_2 + H_2O \rightleftarrows$$

All amines behave as weak bases and form salts when they react with acids such as HCl:

General reaction: $\underset{\text{amine}}{R—NH_2} + \underset{\text{acid}}{HCl} \rightarrow \underset{\text{amine salt}}{R—NH_3^+Cl^-}$ (16.5)

Specific example: $\underset{\text{methylamine}}{CH_3—NH_2} + \underset{\text{acid}}{HCl} \rightarrow \underset{\text{methylammonium chloride}}{CH_3—NH_3^+Cl^-}$ (16.6)

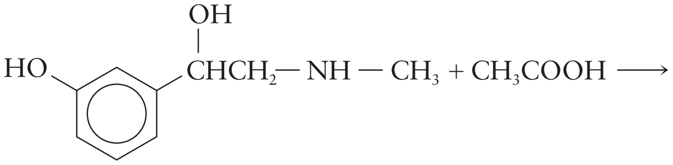
Other acids, such as sulfuric, nitric, phosphoric, and carboxylic acids (Reaction 16.7), also react with amines to form salts:

$$\underset{\text{ethylamine}}{CH_3CH_2{-}NH_2} + \underset{\text{acetic acid}}{CH_3COOH} \rightarrow \underset{\text{ethylammonium acetate}}{CH_3CH_2{-}NH_3{}^+CH_3COO^-} \qquad (16.7)$$

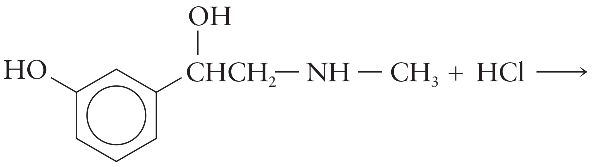
Example 16.7 More Completing Reactions

Phenylephrine is a medication used as a decongestant, to dilate the pupil of the eye, and to increase blood pressure. Complete the following reactions:

a.

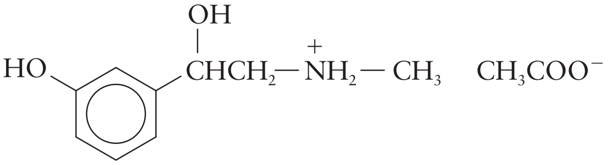


b.

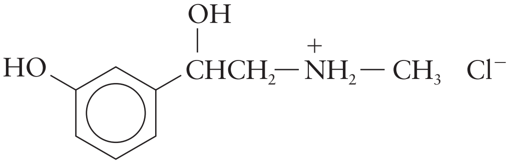


Solution

a. This reaction is similar to reaction 16.7, in which the nitrogen accepts a proton.

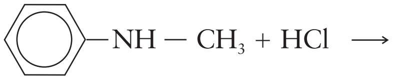


b. This reaction is similar to Key Reaction 16.5.

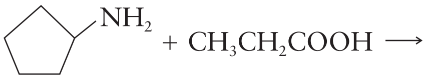


✔ LEARNING CHECK 16.7 Complete the following reactions:

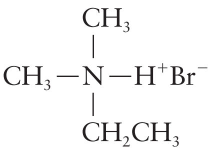
a.



b.



As we have seen, amine salts may be named by changing "amine" to "ammonium" and adding the name of the negative ion derived from the acid. Some more examples are

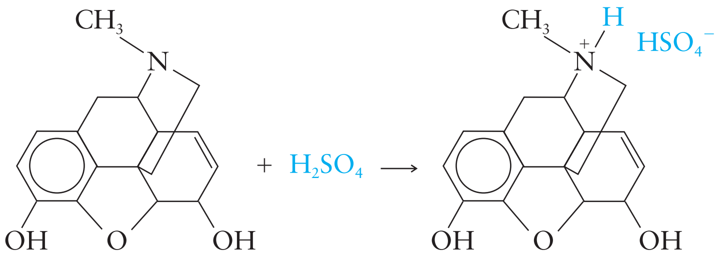


$$CH_3{-}\overset{\displaystyle CH_3}{\underset{\displaystyle CH_2CH_3}{N}}{-}H^+Br^- \qquad (CH_3CH_2)_3NH^+CH_3COO^-$$

ethyldimethylammonium bromide — triethylammonium acetate

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Amine salts have physical properties characteristic of other ionic compounds. They are white crystalline solids with high melting points. Because they are ionic, amine salts are more soluble in water than the parent amines. For this reason, amine drugs are often given in the form of salts so that they will dissolve in body fluids.


(16.8)

morphine
(water insoluble)

morphine sulfate
(water soluble)

Amine salts are easily converted back to amines by adding a strong base:

$$R{-}NH_3^+Cl^- + NaOH \rightarrow R{-}NH_2 + H_2O + NaCl \tag{16.9}$$

The form in which amines occur in solutions is pH dependent, just as is the case for carboxylic acids (see **Section 15.3**). In solutions of high H^+ (low pH), the salt form of amines predominates. In solutions of high OH^- (high pH), the amine form is favored:

$$\underset{\substack{\text{amine}\\ \text{(high pH)}}}{R{-}NH_2} \underset{OH^-}{\overset{H^+}{\rightleftarrows}} \underset{\substack{\text{amine salt}\\ \text{(low pH)}}}{R{-}NH_3^+} \tag{16.10}$$

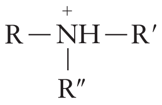
The amine cations in the salts we have discussed to this point have one, two, or three alkyl groups attached to the nitrogen:

$R-NH_3^+$

primary amine
cation

$R-\overset{+}{N}H_2-R'$

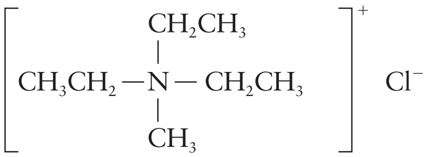
secondary amine
cation



$$R-\overset{+}{\underset{\substack{|\\ R''}}{N}}H-R'$$

tertiary amine
cation

It is also possible to have amine cations in which four alkyl groups or benzene rings are attached to the nitrogen. An example is:



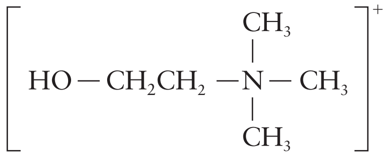
$$\left[CH_3CH_2-\underset{\substack{|\\ CH_3}}{\overset{\substack{CH_2CH_3\\ |}}{N}}-CH_2CH_3 \right]^+ Cl^-$$

triethylmethylammonium chloride

quaternary ammonium salt
An ionic compound containing a positively charged ion in which four alkyl or aromatic groups are bonded to nitrogen, as in R_4N^+.

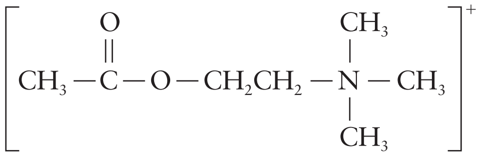
These salts are called **quaternary ammonium salts** and are named the same way as other amine salts. Unlike other amine salts, quaternary salts contain no hydrogen attached to the nitrogen that can be removed by adding a base. Thus, quaternary salts are present in solution in only one form, which is independent of the pH of the solution.

Choline is an important quaternary ammonium ion that is a component of certain lipids (see **Section 18.6**). Acetylcholine is a compound involved in the transmission of nerve impulses from one cell to another (see **Section 16.5**):



$$\left[\mathrm{HO-CH_2CH_2-\underset{CH_3}{\overset{CH_3}{N}}-CH_3}\right]^+$$

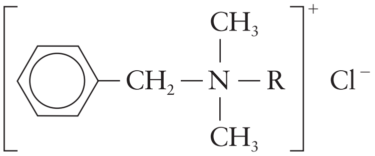
choline cation



$$\left[\mathrm{CH_3-\overset{O}{\overset{\|}{C}}-O-CH_2CH_2-\underset{CH_3}{\overset{CH_3}{N}}-CH_3}\right]^+$$

acetylcholine cation

Some quaternary ammonium salts are important because they have disinfectant properties (see **Figure 16.3**). For example, benzalkonium chloride (Zephiran®) is a well-known antiseptic compound that kills many pathogenic (disease-causing) bacteria and fungi on contact:



Zephiran chloride
(R represents a long alkyl chain)

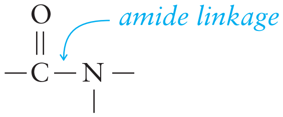
Cristian Gutu/Shutterstock.com

FIGURE 16.3 Quaternary ammonium compounds are used broadly in routine cleaning. In hospitals, quaternary ammonium disinfectants are used on noncritical surfaces such as floors, bed rails, and tray tables.

Its detergent action destroys the membranes that coat and protect the microorganisms. Zephiran chloride is recommended as a disinfectant solution for skin and hands prior to surgery and for the sterile storage of instruments. The trade names of some other anti-infectives that contain quaternary ammonium salts are Phemerol®, Bactine®, and Ceepryn®.

16.4B Amide Formation

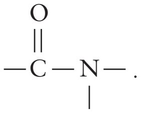
Amines react with acid chlorides or acid anhydrides to form amides. The characteristic functional group of **amides** is a carbonyl group attached to nitrogen. The single bond linking the carbonyl carbon and nitrogen atoms in the group is called an **amide linkage**:



$$-\overset{O}{\overset{\|}{C}}-\underset{|}{N}-$$

amide functional group

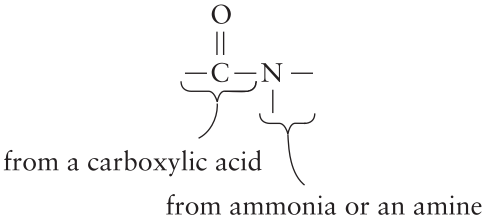
amide An organic compound having the functional group



$$-\overset{O}{\overset{\|}{C}}-\underset{|}{N}-.$$

amide linkage The carbonyl carbon–nitrogen single bond of the amide group.

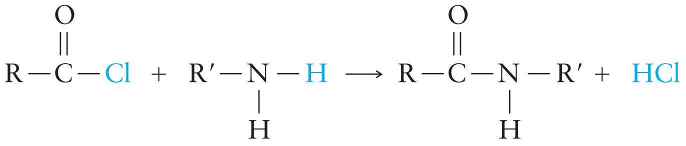
Amides may be thought of as containing an ammonia or amine portion and a portion derived from a carboxylic acid:



However, we've seen that the reaction of an amine with a carboxylic acid normally produces a salt and not an amide. For this reason, the preparation of amides requires the more reactive acid chlorides or acid anhydrides.

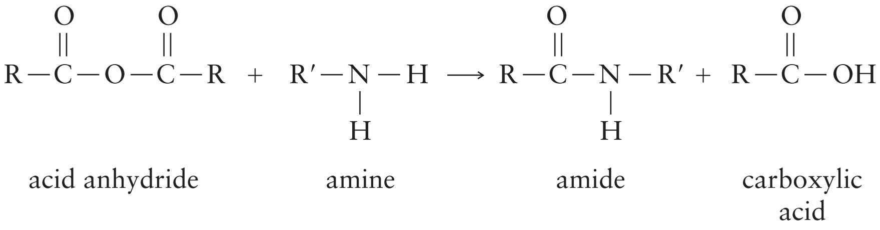
Both primary and secondary amines can be used to prepare amides in this manner, a method similar to the formation of esters (see **Section 15.5**). Tertiary amines, however, do not form amides because they lack a hydrogen atom on the nitrogen.

General reactions:



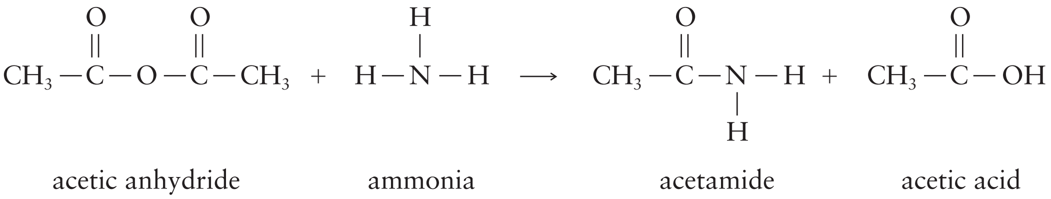
$$\mathrm{R-\overset{O}{\overset{\|}{C}}-Cl + R'-\underset{H}{\underset{|}{N}}-H \longrightarrow R-\overset{O}{\overset{\|}{C}}-\underset{H}{\underset{|}{N}}-R' + HCl} \qquad (16.11)$$

acid chloride amine amide

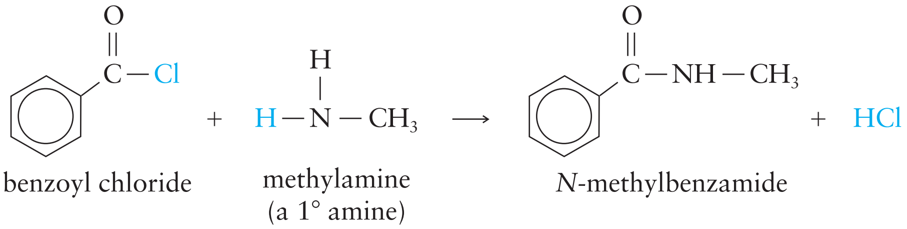

acid anhydride
amine
amide
carboxylic acid

$$R-\overset{\overset{O}{\|}}{C}-O-\overset{\overset{O}{\|}}{C}-R + R'-\underset{\underset{H}{|}}{N}-H \longrightarrow R-\overset{\overset{O}{\|}}{C}-\underset{\underset{H}{|}}{N}-R' + R-\overset{\overset{O}{\|}}{C}-OH \qquad (16.12)$$

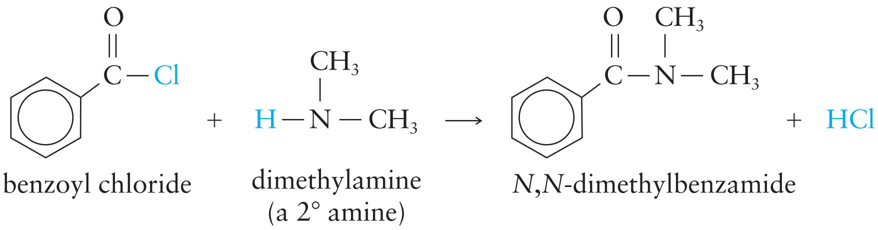
Specific examples:


acetic anhydride
ammonia
acetamide
acetic acid

$$CH_3-\overset{\overset{O}{\|}}{C}-O-\overset{\overset{O}{\|}}{C}-CH_3 + H-\overset{\overset{H}{|}}{N}-H \longrightarrow CH_3-\overset{\overset{O}{\|}}{C}-\underset{\underset{H}{|}}{N}-H + CH_3-\overset{\overset{O}{\|}}{C}-OH \qquad (16.13)$$


benzoyl chloride
methylamine
(a 1° amine)
N-methylbenzamide

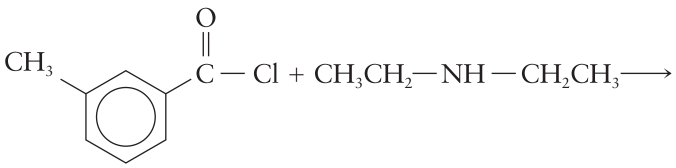
(16.14)


benzoyl chloride
dimethylamine
(a 2° amine)
N,N-dimethylbenzamide

(16.15)

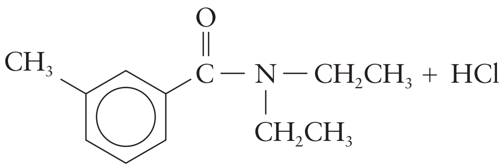
Example 16.8 Preparing Amides

(N,N-Diethyl-meta-toluamide) is one of the few insecticides effective in warding off mosquitoes. Complete the following reaction to show the synthesis of DEET.



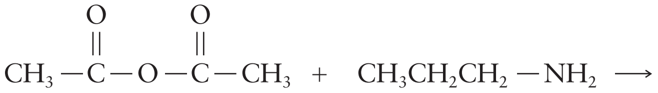
Solution

This reaction is similar to reaction 16.15, producing

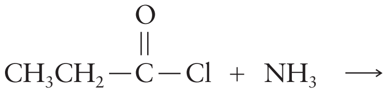


Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

✔ **LEARNING CHECK 16.8** Complete the following reactions:

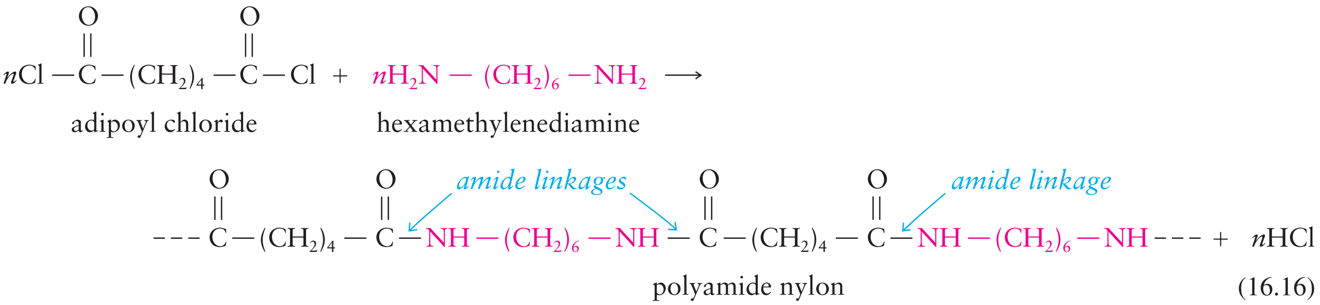
a. 

$$CH_3-\overset{\overset{\large O}{\|}}{C}-O-\overset{\overset{\large O}{\|}}{C}-CH_3 + CH_3CH_2CH_2-NH_2 \longrightarrow$$

b. 

$$CH_3CH_2-\overset{\overset{\large O}{\|}}{C}-Cl + NH_3 \longrightarrow$$

Reaction of diacid chlorides with diamines produces polyamides that, like polyesters, are condensation polymers. The repeating units in polyamides are held together by amide linkage. An example is the formation of nylon, shown in Reaction 16.16 and **Figure 16.4**.



$$n\,Cl-\overset{\overset{\large O}{\|}}{C}-(CH_2)_4-\overset{\overset{\large O}{\|}}{C}-Cl + n\,H_2N-(CH_2)_6-NH_2 \longrightarrow$$

$$---\overset{\overset{\large O}{\|}}{C}-(CH_2)_4-\overset{\overset{\large O}{\|}}{C}-NH-(CH_2)_6-NH-\overset{\overset{\large O}{\|}}{C}-(CH_2)_4-\overset{\overset{\large O}{\|}}{C}-NH-(CH_2)_6-NH--- + n\,HCl$$

(16.16)

Three billion pounds of nylon and related polyamides are produced annually. About 60% of that total goes to make the nylon fiber used in home furnishings such as carpet. The remainder is used largely as a textile fiber in clothing (shirts, dresses, stockings, underwear, etc.) and as tire cord. Minor but important uses include fasteners, rope, parachutes, paintbrushes, and electrical parts (see **Figure 16.5**). In medicine, nylon is used in specialized

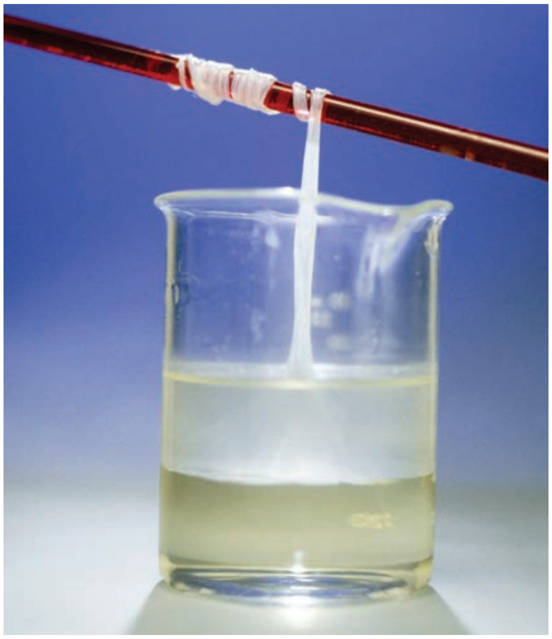


FIGURE 16.4 The preparation of nylon. The reactants occupy separate immiscible layers. Hexamethylenediamine is dissolved in water (bottom layer), and adipoyl chloride is dissolved in hexane (top layer). The two compounds react at the interface between the two layers to form a film of nylon, which is lifted by the rod.

Danshutter/Shutterstock.com

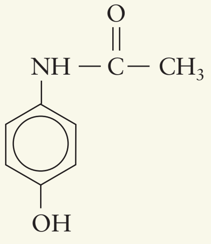
FIGURE 16.5 Parachutes made of nylon fabric.

HEALTH CONNECTIONS **16.1**

Aspirin Substitutes

Even though aspirin is an excellent and useful drug, it occasionally produces adverse effects that cannot be tolerated by some people. These effects include gastrointestinal bleeding and such allergic reactions as skin rashes and asthmatic attacks. Children who are feverish with influenza or chickenpox should not be given aspirin because of a strong correlation with Reye's syndrome, a devastating illness characterized by liver and brain dysfunction.

The amide *acetaminophen*, marketed under trade names such as Tylenol®, Excedrin Aspirin Free®, Panadol®, and Anacin-3®, is an effective aspirin substitute available for use in such situations. Acetaminophen does not irritate the intestinal tract and yet has comparable analgesic (pain-relieving) and antipyretic (fever-reducing) effects. Acetaminophen is available in a stable liquid form suitable for administration to children and other patients who have difficulty taking tablets or capsules. Unlike aspirin, acetaminophen has virtually no anti-inflammatory effect and is therefore a poor substitute for aspirin in the treatment of inflammatory disorders such as rheumatoid arthritis. The overuse of acetaminophen has been linked to liver and kidney damage.



acetaminophen

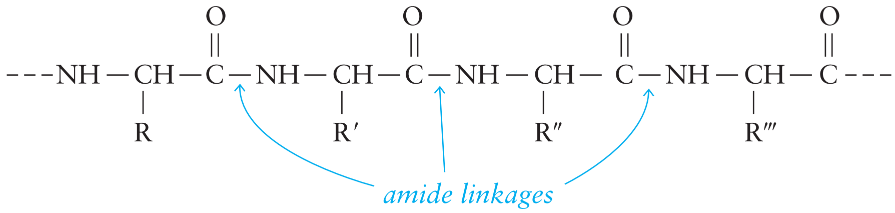
Ibuprofen, a carboxylic acid rather than an amide, is a drug with analgesic, antipyretic, and anti-inflammatory properties that was available for decades only as a prescription drug under the trade name Motrin®.

In 1984, it became available in an over-the-counter (OTC) form under trade names such as Advil®, Ibuprin®, Medipren®, and Motrin IB®. Ibuprofen is thought to be somewhat superior to aspirin as an anti-inflammatory drug, but it has about the same effectiveness as aspirin in relieving mild pain and reducing fever.

In 1994, the FDA approved another compound for sale as an over-the-counter pain reliever. *Naproxen*, marketed under the trade names Aleve® and Anaprox®, exerts its effects for a longer time in the body (8–12 hours per dose) than ibuprofen (4–6 hours per dose) or aspirin and acetaminophen (4 hours per dose). However, the chances for causing slight intestinal bleeding and stomach upset are greater with naproxen than with ibuprofen, and naproxen is not recommended for use by children under age 12.

tubing. Nylon sutures were the first synthetic sutures and are still used. Kevlar, another polyamide (see **Figure 16.6**) is known for its use in protective vests and in many other applications where both toughness and light weight are important.

Silk and wool are natural polyamides that we classify as proteins (see **Chapter 19** for a detailed discussion). For now, note the repeating units and amide linkages characteristic of proteins as shown in the following portion of a polyamide protein chain:



$$---\mathrm{NH}-\underset{\displaystyle \mathrm{R}}{\underset{|}{\mathrm{CH}}}-\overset{\displaystyle \mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{NH}-\underset{\displaystyle \mathrm{R'}}{\underset{|}{\mathrm{CH}}}-\overset{\displaystyle \mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{NH}-\underset{\displaystyle \mathrm{R''}}{\underset{|}{\mathrm{CH}}}-\overset{\displaystyle \mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{NH}-\underset{\displaystyle \mathrm{R'''}}{\underset{|}{\mathrm{CH}}}-\overset{\displaystyle \mathrm{O}}{\overset{\|}{\mathrm{C}}}---$$

amide linkages

Hagley Archive/Science Source

FIGURE 16.6 Stephanie Kwolek, an organic chemist, invented Kevlar in 1965 while working at Dupont.

16.5 Amines as Neurotransmitters

Learning Objective 5 Name amines used as neurotransmitters.

Neurotransmitters, the chemical messengers of the nervous system, carry nerve impulses from one nerve cell (neuron) to another. A neuron consists of a bulbous body called the

neurotransmitter A substance that acts as a chemical bridge in nerve impulse transmission between nerve cells.

soma (or cell body) attached to a long stemlike projection called an axon (see **Figure 16.7**). Numerous short extensions called dendrites are attached to the large bulbous end of the soma, and filaments called synaptic terminals are attached to the end of the axon. At low magnification, the synaptic terminals of one neuron's axon appear to be attached to the dendrites of an adjacent neuron. However, upon further magnification, a small gap called a synapse is visible between the synaptic terminals of the axon and the dendrites of the next neuron.

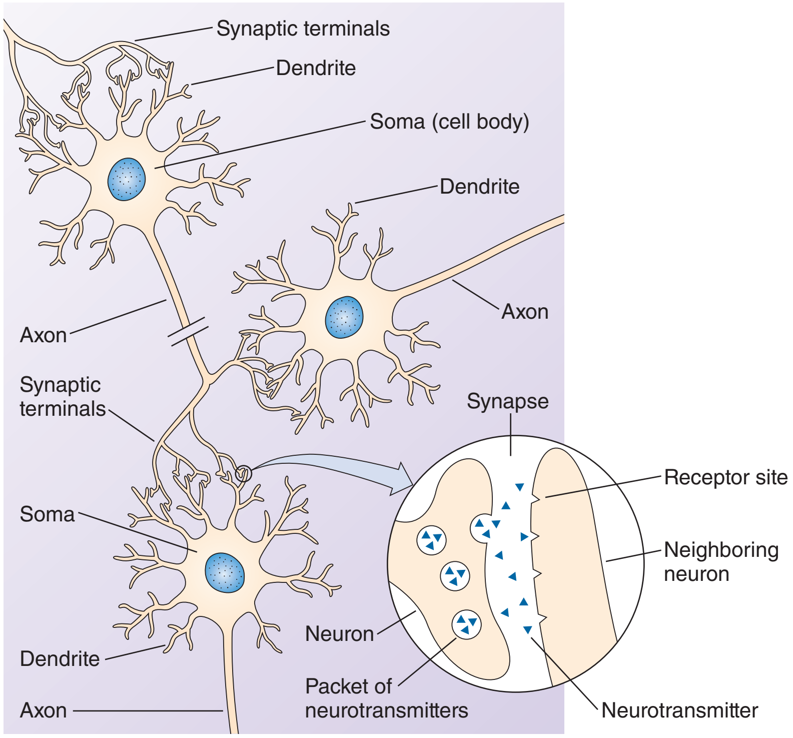
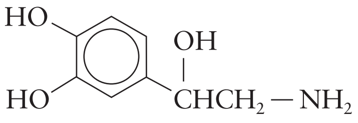
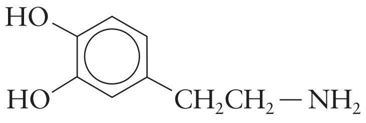


FIGURE 16.7 A nerve cell and the transmission of a nerve signal.

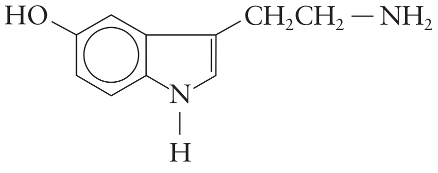
Molecules of a neurotransmitter are stored in small pockets in the axon near the synapse. These pockets release neurotransmitter molecules into the synapse when an electrical current flows from the soma, along the axon to the synaptic terminals. The electrical current is generated by the exchange of positive and negative ions across membranes. The released neurotransmitter molecules diffuse across the synapse and bind to receptors on the dendrites of the next neuron. Once the neurotransmitter binds to the receptor, the message has been delivered. The receiving cell then sends an electrical current down its own axon until a synapse is reached, and a neurotransmitter delivers the message across the synapse to the next neuron. In the central nervous system—the brain and spinal cord—the most important neurotransmitters are acetylcholine and three other amines: norepinephrine, dopamine, and serotonin:



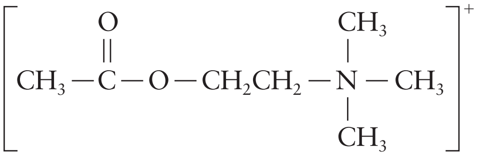
norepinephrine



dopamine



serotonin



$$\left[CH_3-\overset{O}{\overset{\|}{C}}-O-CH_2CH_2-\overset{CH_3}{\underset{CH_3}{N}}-CH_3 \right]^+$$

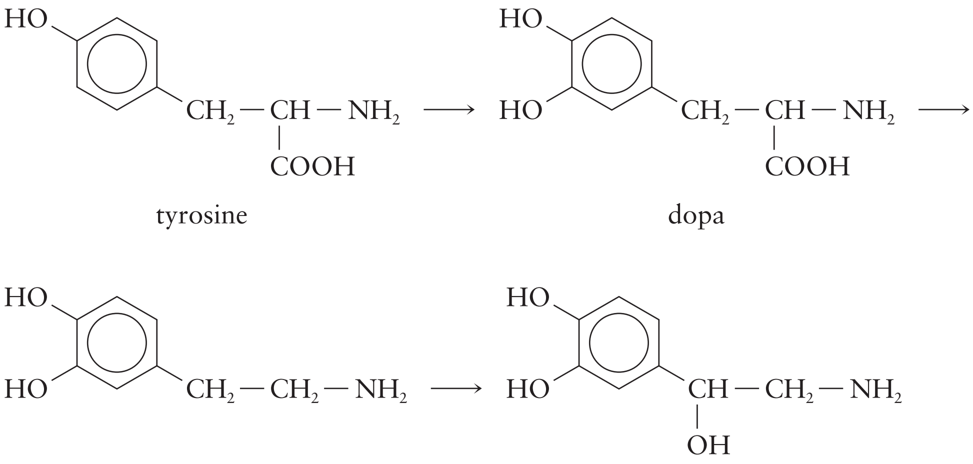
acetylcholine cation

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Neurotransmitters are not only chemical messengers for the nervous system, they may also be partly responsible for our moods. A simplified biochemical theory of mental illness is based on two amines found in the brain. The first is norepinephrine (NE). When an excess of norepinephrine is formed in the brain, the result is a feeling of elation. Extreme excesses of NE can even induce a manic state, while low NE levels may be a cause of depression.

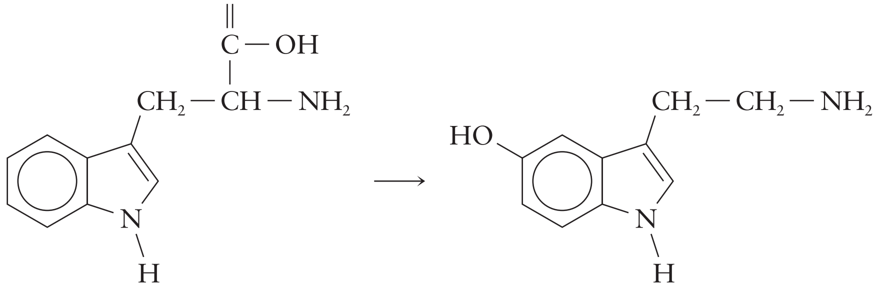
At least six different receptors in the body can be activated by norepinephrine and related compounds. A class of drugs called beta blockers reduces the stimulant action of epinephrine and norepinephrine on various kinds of cells. Some beta blockers are used to treat cardiac arrhythmias, angina, and hypertension (high blood pressure). They function by slightly decreasing the force of each heartbeat. Depression is sometimes a side effect of using such drugs.

In a complex, multistep process, the amino acid tyrosine is used in the body to synthesize norepinephrine:



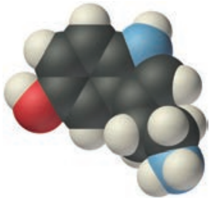
Each step in the process is catalyzed by at least one enzyme, and each of the intermediates formed in the synthesis has physiological activity. Dopa is used as a treatment for Parkinson's disease, and dopamine has been used to treat low blood pressure. Tyrosine is an essential amino acid that must be obtained from the diet, so what we eat may make a direct contribution to our mental health.

The second amine often associated with the biochemical theory of mental illness is serotonin. Like norepinephrine, it also functions as a neurotransmitter. Serotonin is produced in the body from the amino acid tryptophan:



tryptophan

serotonin



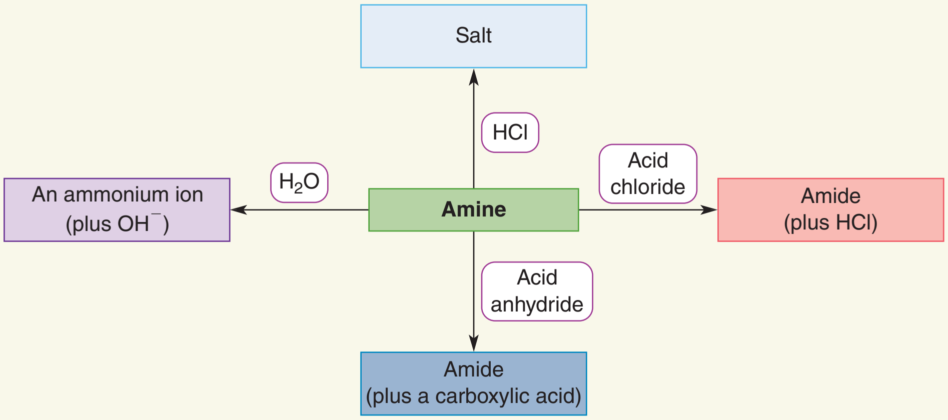
Serotonin

Serotonin has been found to influence sleeping, the regulation of body temperature, and sensory perception, but its exact role in mental illness is not yet clear. Unusually low levels of 5-hydroxyindoleacetic acid, a product of serotonin utilization, are characteristically found in the spinal fluid of victims of violent suicide. Drugs that mimic serotonin are

STUDY TOOLS 16.1

A Reaction Map for Amines

We have discussed four different reactions of amines. When trying to decide what happens in a reaction, remember to focus on the functional groups. After identifying an amine as a starting material, next decide what other reagent is involved and which of the four pathways is appropriate.



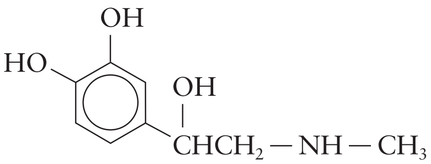
sometimes used to treat depression, anxiety, and obsessive–compulsive disorder. Serotonin blockers are used to treat migraine headaches and relieve the nausea that accompanies cancer chemotherapy. A better understanding of the biochemistry of the brain may lead to better medications for treating various forms of mental illness.

16.6 Other Biologically Important Amines

Learning Objective 6 Give uses for specific biological amines.

16.6A Epinephrine

Epinephrine, or adrenaline, has a molecular structure similar to that of norepinephrine. The difference is that epinephrine contains an *N*-methyl group:



epinephrine
(adrenaline)

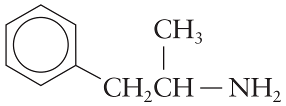
Epinephrine is more important as a hormone than as a neurotransmitter. It is synthesized in the adrenal gland and acts to increase the blood level of glucose, a key source of energy for body processes. The release of epinephrine—usually in response to pain, anger, or fear—provides glucose for a sudden burst of energy. For this reason, epinephrine has been called the fight-or-flight hormone.

Epinephrine also raises blood pressure. It does this by increasing the rate and force of heart contractions and by constricting the peripheral blood vessels. Injectable local anesthetics usually contain epinephrine because it constricts blood vessels in the vicinity of the injection. This prevents the blood from rapidly "washing" the anesthetic away and prolongs the anesthetic effect in the target tissue. Epinephrine is also used to reduce hemorrhage, treat asthma attacks, and combat anaphylactic shock (collapse of the circulatory system).

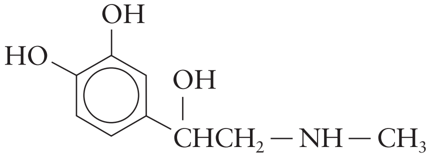
16.6B Amphetamines

Amphetamine (also known as Benzedrine®) is a powerful nervous system stimulant with an amine structure similar to that of epinephrine:

Amphetamine



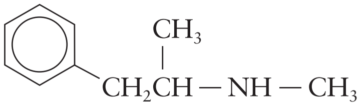
amphetamine
(Benzedrine)



epinephrine
(adrenaline)

Notice that both compounds contain an aromatic ring attached to a substituted ethylamine. That structural arrangement, sometimes referred to as a phenethylamine, is apparently an essential feature of several physiologically active compounds. These structural similarities lead to similar behaviors in the body: Both compounds raise the glucose level in the blood and increase pulse rate and blood pressure. Other closely related phenethylamine compounds, such as Methedrine®, also act as powerful nervous system stimulants. Compounds of this type can be thought of as being derived from amphetamine and as a result are sometimes collectively referred to as **amphetamines**:

amphetamines A class of drugs structurally similar to epinephrine, used to stimulate the central nervous system.



N-methylamphetamine
(Methedrine, or "speed")

Amphetamines are used both legally (as prescribed by a physician) and illegally to elevate mood or reduce fatigue. In the drug culture, amphetamine tablets go by such names as bennies, pep pills, reds, red devils, speed, dexies, and uppers. Some amphetamines (known as STP, speed, and mescaline) cause hallucinations. The abuse of such drugs results in severe detrimental effects on both the body and the mind. They are addictive and concentrate in the brain and nervous system. Abusers often experience long periods of sleeplessness, weight loss, and paranoia. Abusers of amphetamines often compound their problems by taking other drugs in order to prevent the "crash," or deep depression, brought on by discontinuation of the drug.

Anna Sapykina/Shutterstock.com

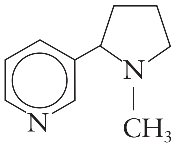
FIGURE 16.8 Common daffodil bulbs are poisonous if eaten because of the presence of powerful alkaloids.

16.6C Alkaloids

Plants are the sources of some of the most powerful drugs known (see **Figure 16.8**). Numerous indigenous people in the world possess knowledge about the physiological effects that result from eating or chewing the leaves, roots, flowers, or bark of certain plants. The effects vary from plant species to plant species. Some cure diseases; others, such as opium, are addictive drugs. Still others are deadly poisons, such as the leaves of the belladonna plant and the hemlock herb. The substances responsible for these marked physiological effects are often nitrogen-containing compounds called **alkaloids**. The name, which means alkali-like, reflects the fact that these amine compounds are weakly basic.

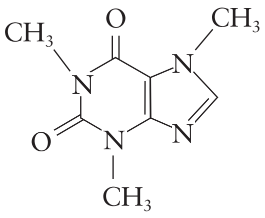
alkaloids A class of nitrogen-containing organic compounds obtained from plants.

The molecular structures of alkaloids vary from simple to complex. Two common and relatively simple alkaloids are nicotine, which is found in tobacco, and caffeine, which is present in coffee and cola drinks:

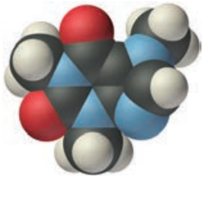


nicotine

Nicotine



caffeine



Caffeine

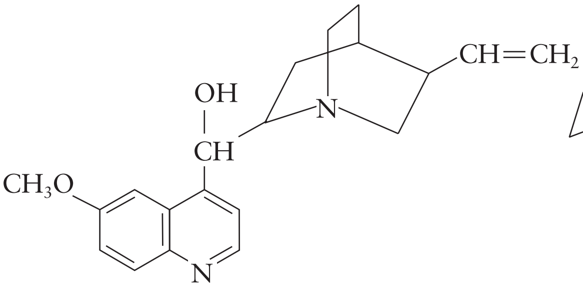
Many people absorb nicotine into their bodies as a result of smoking or chewing tobacco. In small doses, nicotine behaves like a stimulant and is not especially harmful. However, it is habit-forming, and habitual tobacco users are exposed to other harmful substances such as tars, carbon monoxide, and polycyclic carcinogens.

Besides coffee and cola drinks, other sources of caffeine are tea (see **Figure 16.9**), chocolate, and cocoa. Caffeine is a mild stimulant of the respiratory and central nervous systems, the reason for its well-known side effects of nervousness and insomnia. These characteristics, together with its behavior as a mild diuretic, account for the use of caffeine in a wide variety of products, including pain relievers, cold remedies, diet pills, and "stay-awake" pills (No-Doz®). Because caffeine is considered to be a drug, pregnant women should be prudent about how much caffeine they consume. Like most other drugs, caffeine enters the bloodstream, crosses the placental barrier, and reaches the fetus.

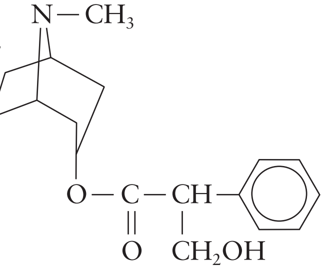
iStock.com/Tom Merton

FIGURE 16.9 Tea is a common source of caffeine.

A number of alkaloids are used medicinally. Quinine, for example, is used to treat malaria. Atropine is used as a preoperative drug to relax muscles and reduce the secretion of saliva in surgical patients, and to dilate the pupil of the eye in patients undergoing eye examinations.



quinine

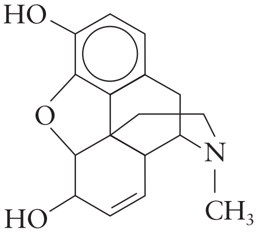


atropine

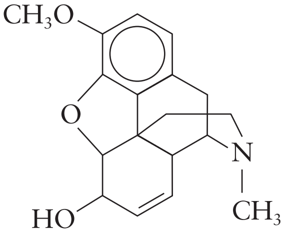
Opium, the dried juice of the poppy plant (see **Figure 16.10**), has been used for centuries as a painkilling drug. It contains numerous alkaloids, including morphine and its methyl ether, codeine. Both are central nervous system depressants, with codeine being much weaker. They exert a soothing effect on the body when administered in sufficient amounts. These properties make them useful as painkillers. Morphine is especially useful in this regard, being one of the most effective painkillers known. Codeine is used in some cough syrups to depress the action of the cough center in the brain. The major drawback to using these drugs is that they are all addictive. Heroin, a derivative of morphine, is one of the more destructive, illegally-used hard drugs. Although intended at one time as a less-addictive substitute for morphine, heroin is actually much more addictive than morphine and has no accepted medical use in the United States.

Soru Epotok/Shutterstock.com

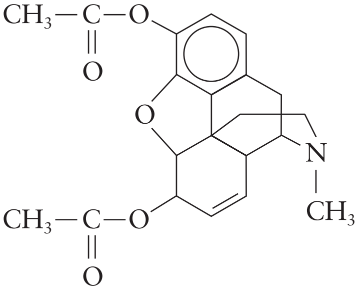
FIGURE 16.10 Since ancient times, the milky fluid that seeps from cuts on the unripe poppy seed pod has been air-dried to produce opium.



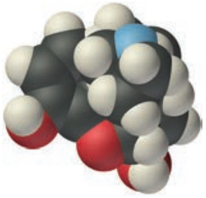
morphine



codeine



heroin



Morphine

HEALTH CONNECTIONS **16.2**

Try a Little Chocolate

Chocolate has a history that goes back beyond 1492, when Columbus arrived on the American continent. Chocolate in various forms is prepared from the seeds of the cacao plant. The seeds are roasted, husked, and then ground into a powder. The Mayan word "cacao" comes from two Mayan words that together mean "bitter juice." The Mayans were able to convert this bitter material into a form that we, today, call chocolate.

Like other rich foods, chocolate is regarded by many as an indulgence or guilty pleasure. Because of its high sugar and fat content, chocolate has been associated with health problems such as obesity, acne, diabetes, heart disease, and tooth decay. But scientists are now discovering health benefits, and they are offering some justification for including chocolate in a healthy diet.

Some recent studies correlate chocolate consumption with reduced cardiovascular disease, lower blood pressure, lower cholesterol levels, and improved cognition and memory.

Most of the world's chocolate is grown in a narrow area of the world located 10 degrees on either side of the equator (mostly in West Africa). The word "chocolate" can refer to anything from white chocolate to milk chocolate. However, the chocolate that provides the most health benefits is *dark* chocolate. Dark chocolate is rich in phenolic compounds called flavonoids. Flavonoids are also found in fruits, vegetables, tea, red wine, and beer. The flavonoids in chocolate are powerful antioxidants that protect cells against oxidation damage. Darker chocolate has a higher flavonoid content than lighter varieties. So, if you are seeking health benefits from chocolate, the darker the chocolate, the better.

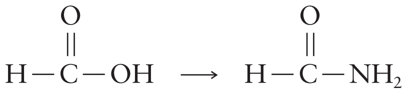
Aleksandrs Samuilovs/Shutterstock.com

Dark chocolate can be part of a healthy diet.

16.7 The Nomenclature of Amides

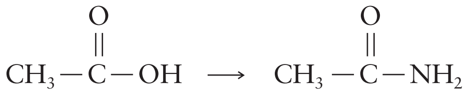
Learning Objective 7 Assign IUPAC names for amides.

Simple amides are named after the corresponding carboxylic acids by changing the *-ic* ending (common names) or the *-oic* ending (IUPAC names) of the acid to *-amide*. Common names are used more often than IUPAC names. Some examples of the assignment of such names follow:



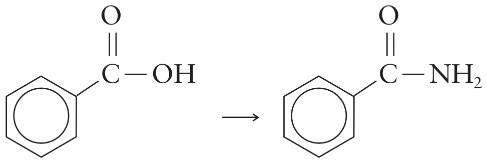
$$\mathrm{H-\overset{\overset{\large O}{\|}}{C}-OH} \longrightarrow \mathrm{H-\overset{\overset{\large O}{\|}}{C}-NH_2}$$

Common name	formic acid	formamide
IUPAC name	methanoic acid	methanamide



$$\mathrm{CH_3-\overset{\overset{\large O}{\|}}{C}-OH} \longrightarrow \mathrm{CH_3-\overset{\overset{\large O}{\|}}{C}-NH_2}$$

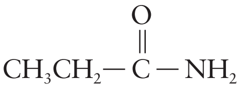
Common name	acetic acid	acetamide
IUPAC name	ethanoic acid	ethanamide



Common name	benzoic acid	benzamide
IUPAC name	benzoic acid	benzamide

Example 16.9 Naming Amides

Give an IUPAC name to the following amide:



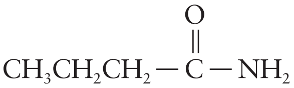
$$CH_3CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2$$

Solution

The chain of carbon atoms is three; the name is propanamide.

✔ LEARNING CHECK 16.9

a. Give the IUPAC name for the following simple amide:

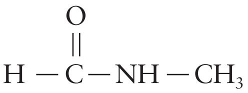
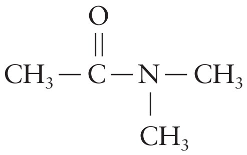
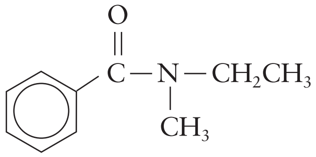


$$CH_3CH_2CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2$$

b. What is the IUPAC name for the simple amide derived from hexanoic acid?

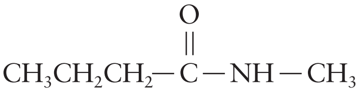
If alkyl groups are attached to the nitrogen atom of amides (substituted amides), the name of the alkyl group precedes the name of the amide, and an italic capital *N* is used to indicate that the alkyl group is bonded to the nitrogen.

See the following examples.

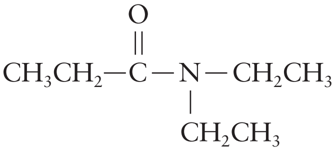
	 $H-\overset{\overset{O}{\|}}{C}-NH-CH_3$	 $CH_3-\overset{\overset{O}{\|}}{C}-\underset{\underset{CH_3}{\mid}}{N}-CH_3$	
Common name	*N*-methylformamide	*N*,*N*-dimethylacetamide	*N*-ethyl-*N*-methylbenzamide
IUPAC name	*N*-methylmethanamide	*N*,*N*-dimethylethanamide	*N*-ethyl-*N*-methylbenzamide

Example 16.10 More Naming Amides

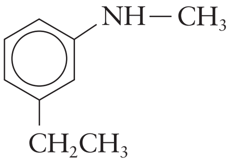
Give either a common name or the IUPAC name for each of the following amides:

a. 

$$CH_3CH_2CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-NH-CH_3$$

b. 

$$CH_3CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-\underset{\underset{\displaystyle CH_2CH_3}{\mid}}{N}-CH_2CH_3$$

c. 

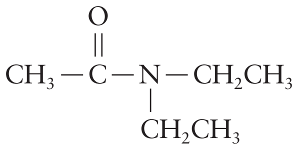
Solution

a. The common name for the acid, butyric acid is found in **Table 15.1**. The common name for the amide is *N*-methylbutyramide. The IUPAC name is *N*-methylbutanamide.

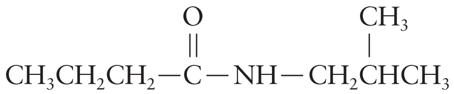
b. The common name is *N,N*-diethylpropionamide. The IUPAC name is *N,N*-diethylpropanamide.

c. 3-ethyl-*N*-methylaniline

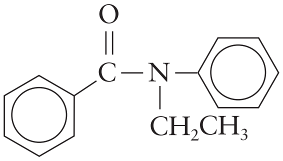
✔ LEARNING CHECK 16.10 Give either a common name or the IUPAC name for each of the following amides:

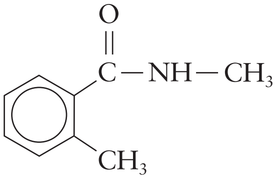
a.


$CH_3-\overset{\overset{\displaystyle O}{\parallel}}{C}-\underset{\underset{\displaystyle CH_2CH_3}{|}}{N}-CH_2CH_3$

b.


$CH_3CH_2CH_2-\overset{\overset{\displaystyle O}{\parallel}}{C}-NH-CH_2\overset{\overset{\displaystyle CH_3}{|}}{C}HCH_3$

c.


d.


16.8 Physical Properties of Amides

Learning Objective 8 Show the formation of hydrogen bonds with amides.

Formamide is a liquid at room temperature. It is the only unsubstituted amide that is a liquid; all others are solids.

Unsubstituted amides can form a complex network of intermolecular hydrogen bonds (see **Figure 16.11**). It is this characteristic that causes melting points of these substances to be so high.

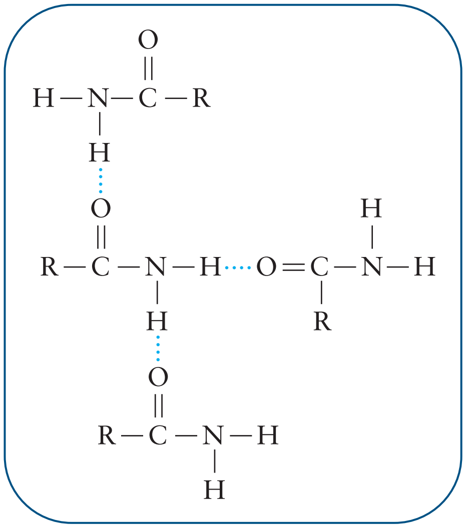
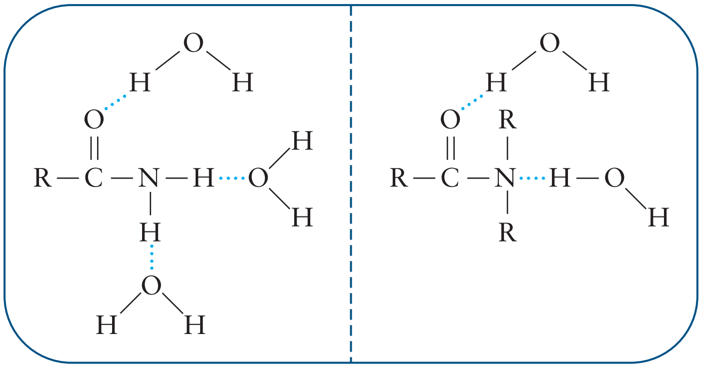


FIGURE 16.11 Intermolecular hydrogen bonding in an unsubstituted amide.

The substitution of alkyl or aromatic groups for hydrogen atoms on the nitrogen reduces the number of intermolecular hydrogen bonds that can form and causes the melting points to decrease. Thus, disubstituted amides often have lower melting and boiling points than monosubstituted and unsubstituted amides. We will see in Chapter 19 that hydrogen bonding between amide groups is important in maintaining the shape of protein molecules.

Amides are rather water soluble, especially those containing fewer than six carbon atoms. This solubility results from the ability of amides to form hydrogen bonds with water. Even disubstituted amides do this because of the presence of the carbonyl oxygen (see **Figure 16.12**).



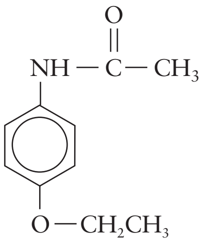
a an unsubstituted amide

b a disubstituted amide

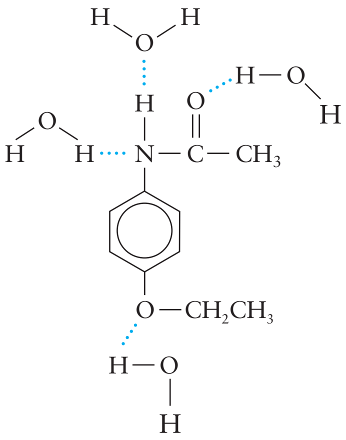
FIGURE 16.12 Hydrogen bonding between water.

Example 16.11 Showing Hydrogen Bonding

Phenacetin, a pain-relieving drug removed from medicinal use in the 1970s, has the structure below. Show how phenacetin form hydrogen bonds with water molecules.



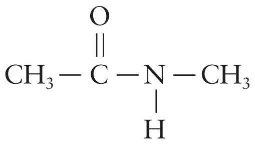
Solution



✔ LEARNING CHECK 16.11 Show how the amide below can form the following:

a. Intermolecular hydrogen bonds with other amide molecules

b. Hydrogen bonds with water molecules



$$CH_3-\overset{\overset{\Large O}{\|}}{C}-\underset{\underset{\Large H}{|}}{N}-CH_3$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

16.9 Chemical Properties of Amides

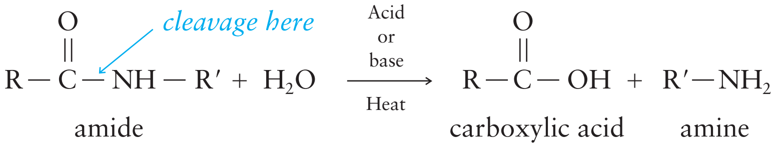
Learning Objective 9 Give the products of acidic and basic hydrolysis of amides.

16.9A Neutrality

Because basicity is the most important property of amines, it is only natural to wonder if amides are also basic. The answer is no. Although they are formed from carboxylic acids and basic amines, amides are neither basic nor acidic; they are neutral. The carbonyl group bonded to the nitrogen has destroyed the basicity of the original amine, and the nitrogen of the amine has replaced the acidic —OH of the carboxylic acid.

16.9B Amide Hydrolysis

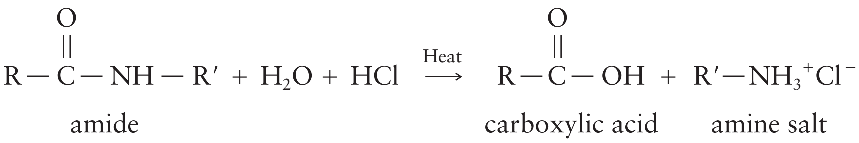
The most important reaction of amides is hydrolysis. This reaction corresponds to the reverse of amide formation; the amide is cleaved into two compounds, a carboxylic acid and an amine or ammonia:



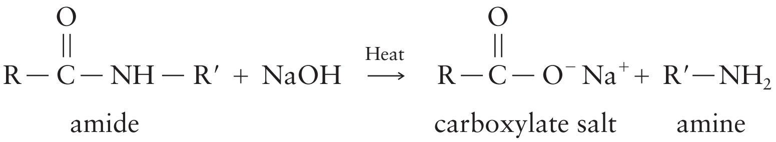
$$\underset{\text{amide}}{\mathrm{R{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}NH{-}R'}} + \mathrm{H_2O} \xrightarrow[\text{Heat}]{\text{Acid or base}} \underset{\text{carboxylic acid}}{\mathrm{R{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}OH}} + \underset{\text{amine}}{\mathrm{R'{-}NH_2}} \quad (16.17)$$

As with hydrolysis of carboxylic esters, amide hydrolysis requires the presence of a strong acid or base, and the nature of the final products depends on which of these reactants is used. Notice in the following examples that under acidic conditions, the salt of the amine is produced along with the carboxylic acid, and under basic conditions, the salt of the carboxylic acid is formed along with the amine. Also, notice that heat is required for the hydrolysis of amides.

General reactions:

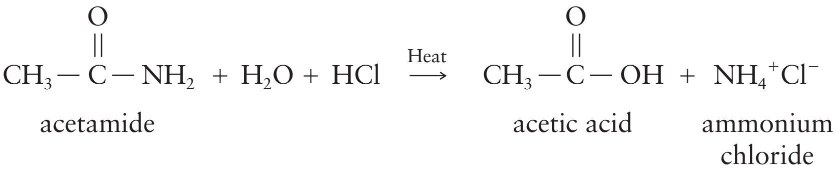


$$\underset{\text{amide}}{\mathrm{R{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}NH{-}R'}} + \mathrm{H_2O} + \mathrm{HCl} \xrightarrow{\text{Heat}} \underset{\text{carboxylic acid}}{\mathrm{R{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}OH}} + \underset{\text{amine salt}}{\mathrm{R'{-}NH_3{}^+Cl^-}} \quad (16.18)$$

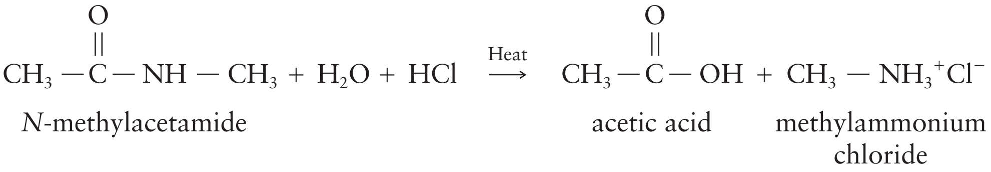


$$\underset{\text{amide}}{\mathrm{R{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}NH{-}R'}} + \mathrm{NaOH} \xrightarrow{\text{Heat}} \underset{\text{carboxylate salt}}{\mathrm{R{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}O^-Na^+}} + \underset{\text{amine}}{\mathrm{R'{-}NH_2}} \quad (16.19)$$

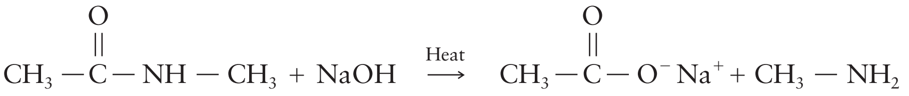
Specific examples:



$$\underset{\text{acetamide}}{\mathrm{CH_3{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}NH_2}} + \mathrm{H_2O} + \mathrm{HCl} \xrightarrow{\text{Heat}} \underset{\text{acetic acid}}{\mathrm{CH_3{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}OH}} + \underset{\text{ammonium chloride}}{\mathrm{NH_4{}^+Cl^-}} \quad (16.20)$$



$$\underset{N\text{-methylacetamide}}{\mathrm{CH_3{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}NH{-}CH_3}} + \mathrm{H_2O} + \mathrm{HCl} \xrightarrow{\text{Heat}} \underset{\text{acetic acid}}{\mathrm{CH_3{-}\overset{\overset{\displaystyle O}{\|}}{C}{-}OH}} + \underset{\text{methylammonium chloride}}{\mathrm{CH_3{-}NH_3{}^+Cl^-}} \quad (16.21)$$



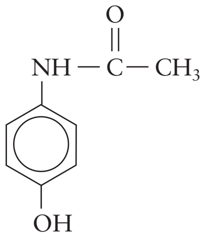
$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-NH-CH_3 + NaOH \xrightarrow{\text{Heat}} CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-O^-Na^+ + CH_3-NH_2$$ (16.22)

N-methylacetamide sodium acetate methylamine

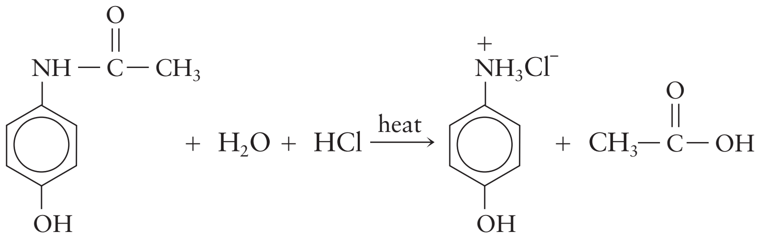
Because the form in which carboxylic acids and amines occur in solution depends on the solution pH, one of the hydrolysis products must always be in the form of a salt.

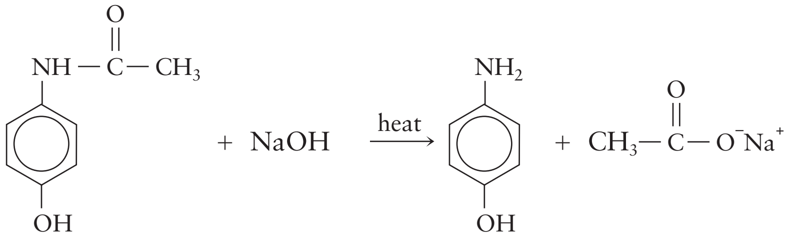
Example 16.12 Writing Hydrolysis Reactions

The structure of acetaminophen, a pain reliever and fever reducer, is shown below. Show the hydrolysis of acetaminophen using HCl and NaOH.



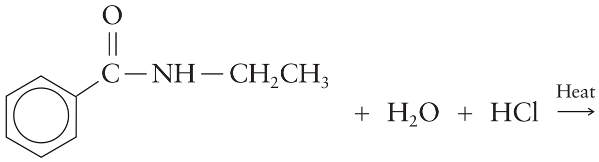
Solution



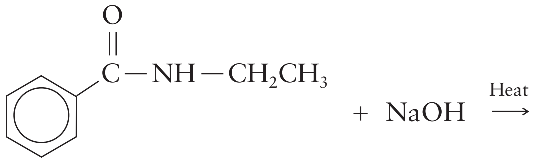


✔ LEARNING CHECK 16.12 Complete the following hydrolysis reactions:

a.



b.

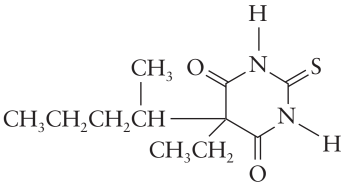
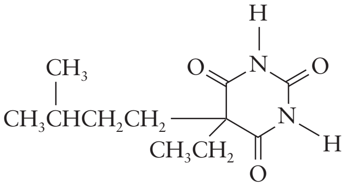
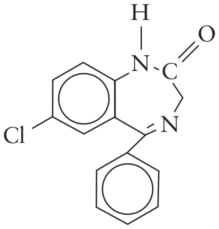
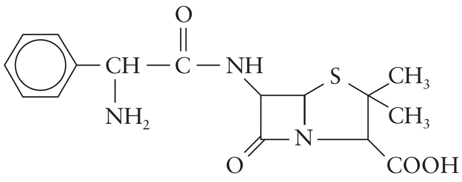


Amide hydrolysis, a very important reaction in biochemistry, is a central reaction in the digestion of proteins and the breakdown of proteins within cells. However, most amide hydrolysis in the body is catalyzed by enzymes rather than by strong acids or bases.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Because of their physiological properties, a number of amides play valuable roles in medicine. **Table 16.3** lists some of these important compounds.

TABLE 16.3 Some Important Amides in Medicine

Structure	Generic Name (Trade Name)	Use
	thiopental (Pentothal®)	Intravenous anesthesia
	amobarbital (Amytal®)	Treatment of insomnia
	diazepam (Valium®)	Tranquilizer
	ampicillin (Polycillin®)	Antibiotic

Health Career Description

ALLERGY/IMMUNOLOGY NURSE

According to DailyNurse.org, "An allergy/immunology nurse focuses on the care of patients with chronic allergic conditions. These conditions include asthma, allergic rhinitis, urticaria, and atopic dermatitis. Duties include providing direct patient care and health education and, in most cases, administrative responsibilities such as those of an Allergy Office Manager."

Because allergies, in rare instances, may be life-threatening, allergy nurses must be certified in basic life support, in addition to holding R.N. certification. Many allergy nurses also hold certification in asthma education from the National Asthma Educator Certification Board.

Most allergy nurses work in clinics that conduct desensitization therapy (allergy shots) and allergen skin testing. Allergy nurses must possess acute observation skills, including the ability to discern slight differences in coloration and to discern slight changes in behavior or physical appearance. They must also be able to differentiate between normal and abnormal breathing sounds and respiration rates.

Allergy nurses must be able to work with patients of all ages and demographics. Communication skills are extremely important. Allergy nurses must observe strict attention to detail and maintain meticulous records.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Knowledge of chemistry and biochemistry is important for the allergy nurse in order to understand the reactions of the human body to proteins it perceives as threatening (as an allergen). Understanding the role of histamine in the body and the way antihistamines work is fundamental to working in the field of immunology.

Allergy nurses must have the ability to remain calm and act quickly in emergency situations and be able to impart calm to stressed patients or family members. Empathy and compassion along with precise technical skills are necessary for the immunological nurse.

Allergies run the gamut from somewhat irritating to highly dangerous. Immunological nurses help patients find their way to a healthier relationship with their environments.

Concept Summary

16.1 Classification of Amines

Learning Objective: Given structural formulas, can you classify amines as primary, secondary, or tertiary?

- Amines are organic derivatives of ammonia in which one or more of the ammonia hydrogens are replaced by alkyl or aromatic groups.
- Amines are classified as primary, secondary, or tertiary, depending on the number of groups (one, two, or three) attached to the nitrogen.

16.2 The Nomenclature of Amines

Learning Objective: Can you assign common and IUPAC names to simple amines?

- Common names are given to simple amines by adding the ending *-amine* to the names of the alkyl groups attached to the nitrogen.
- In IUPAC names, the *-e* ending in the alkane name is changed to *-amine*.
- Aromatic amines are named as derivatives of aniline.

16.3 Physical Properties of Amines

Learning Objective: Can you discuss how hydrogen bonding influences the physical properties of amines?

- Primary and secondary amines have boiling points slightly lower than those of corresponding alcohols.
- Tertiary amines have boiling points similar to those of alkanes.
- Low-molecular-weight amines are water-soluble.

16.4 Chemical Properties of Amines

Learning Objective: Can you recognize and write key reactions for amines?

- Amines are weak bases.
- They react with water to liberate hydroxide ions.
- They react with acids to form salts.
- Amines react with acid chlorides and acid anhydrides to form amides.

16.5 Amines as Neurotransmitters

Learning Objective: Can you name amines used as neurotransmitters?

- Neurotransmitters are the chemical messengers of the nervous system.
- They carry nerve impulses from one nerve cell (neuron) to another.
- The most important neurotransmitters are acetylcholine and three other amines: norepinephrine, dopamine, and serotonin.

16.6 Other Biologically Important Amines

Learning Objective: Can you give uses for specific biological amines?

- Four neurotransmitters are acetylcholine, norepinephrine, dopamine, and serotonin.
- Epinephrine is also known as the fight-or-flight hormone.
- The amphetamines have structures similar to that of epinephrine.
- Alkaloids are nitrogen-containing compounds isolated from plants.
- They exhibit a variety of physiological effects on the body.
- Examples of alkaloids include nicotine, caffeine, quinine, atropine, morphine, and codeine.

16.7 The Nomenclature of Amides

Learning Objective: Can you assign IUPAC names for amides?

- Amides are named by changing the *-ic acid* or *-oic acid* ending of the carboxylic acid portion of the compound to *-amide*.
- Groups attached to the nitrogen of the amide are denoted by an italic capital *N* that precedes the name of the attached group.

16.8 Physical Properties of Amides

Learning Objective: Can you show the formation of hydrogen bonds with amides?

- Low-molecular-weight amides are water-soluble because of the formation of hydrogen bonds.
- The melting and boiling points of unsubstituted amides are higher than those of comparable substituted amides because of intermolecular hydrogen bonding.

16.9 Chemical Properties of Amides

Learning Objective: Can you give the products of acidic and basic hydrolysis of amides?

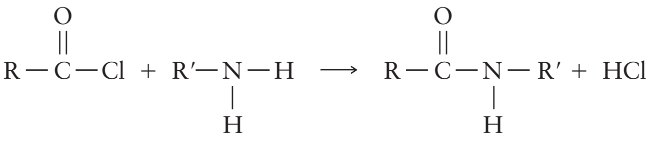
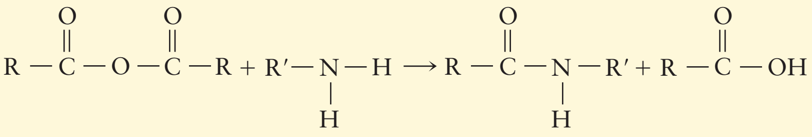
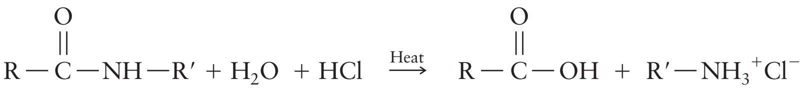
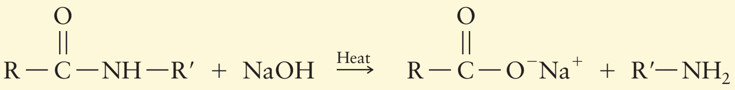
- Amides undergo hydrolysis in acidic conditions to yield a carboxylic acid and an amine salt.
- Hydrolysis under basic conditions produces a carboxylate salt and an amine.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Key Terms and Concepts

Alkaloids (16.6)
Amide (16.4)
Amide linkage (16.4)
Amine (16.1)
Amphetamines (16.6)
Neurotransmitter (16.5)
Primary amine (16.1)
Quaternary ammonium salt (16.4)
Secondary amine (16.1)
Tertiary amine (16.1)

Key Equations

1. Reaction of amines with water (**Section 16.4**):	$R—NH_2 + H_2O \rightleftarrows R—NH_3^+ + OH^-$	Reaction 16.3
2. Reaction of amines with acids (**Section 16.4**):	$R—NH_2 + HCl \rightarrow R—NH_3^+ + Cl^-$	Reaction 16.5
3. Conversion of amine salts back to amines (**Section 16.4**):	$R—NH_3^+Cl^- + NaOH \rightarrow R—NH_2 + H_2O + NaCl$	Reaction 16.9
4. Reaction of amines with acid chlorides to form amides (**Section 16.4**):	 $R-\overset{O}{\overset{\Vert}{C}}-Cl + R'-\underset{H}{\underset{\vert}{N}}-H \longrightarrow R-\overset{O}{\overset{\Vert}{C}}-\underset{H}{\underset{\vert}{N}}-R' + HCl$	Reaction 16.11
5. Reaction of amines with acid anhydrides to form amides (**Section 16.4**):	 $R-\overset{O}{\overset{\Vert}{C}}-O-\overset{O}{\overset{\Vert}{C}}-R + R'-\underset{H}{\underset{\vert}{N}}-H \longrightarrow R-\overset{O}{\overset{\Vert}{C}}-\underset{H}{\underset{\vert}{N}}-R' + R-\overset{O}{\overset{\Vert}{C}}-OH$	Reaction 16.12
6. Acid hydrolysis of amides (**Section 16.9**):	 $R-\overset{O}{\overset{\Vert}{C}}-NH-R' + H_2O + HCl \xrightarrow{\text{Heat}} R-\overset{O}{\overset{\Vert}{C}}-OH + R'-NH_3^+Cl^-$	Reaction 16.18
7. Basic hydrolysis of amides (**Section 16.9**):	 $R-\overset{O}{\overset{\Vert}{C}}-NH-R' + NaOH \xrightarrow{\text{Heat}} R-\overset{O}{\overset{\Vert}{C}}-O^-Na^+ + R'-NH_2$	Reaction 16.19

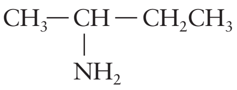
Exercises

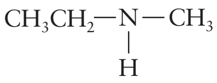
Even-numbered exercises are answered in Appendix B.

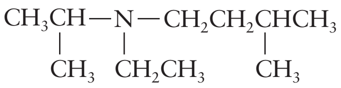
Exercises with an asterisk (*) are more challenging.

Classification of Amines (Section 16.1)

16.1 Identify which of the following compounds has an amine functional group in it:

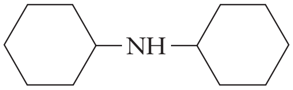
a. 
$CH_3-\underset{NH_2}{\underset{\vert}{CH}}-CH_2CH_3$

b. 
$CH_3CH_2-\underset{H}{\underset{\vert}{N}}-CH_3$

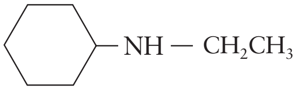
c. 
$CH_3\underset{CH_3}{\underset{\vert}{CH}}-\underset{CH_2CH_3}{\underset{\vert}{N}}-CH_2CH_2\underset{CH_3}{\underset{\vert}{CH}}CH_3$

16.2 Identify which of the following compounds has an amine functional group in it:

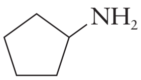
a.



b.



c.

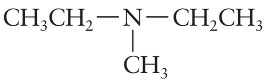


16.3 What is the difference among primary, secondary, and tertiary amines in terms of bonding to the nitrogen atom?

16.4 Give a general formula for a primary amine, a secondary amine, and a tertiary amine.

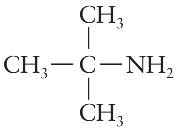
16.5 Classify each of the following as a primary, secondary, or tertiary amine:

a.



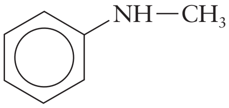
$CH_3CH_2{-}\underset{\substack{|\\ CH_3}}{N}{-}CH_2CH_3$

b.

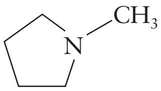


$CH_3{-}\overset{\substack{CH_3\\ |}}{\underset{\substack{|\\ CH_3}}{C}}{-}NH_2$

c.

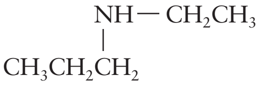


d.



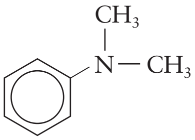
16.6 Classify each of the following as a primary, secondary, or tertiary amine:

a.

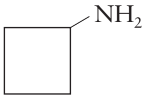


$\overset{\substack{NH-CH_2CH_3\\ |}}{CH_3CH_2CH_2}$

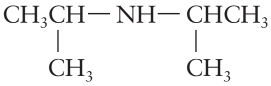
b.



c.



d.



$CH_3\underset{\substack{|\\ CH_3}}{CH}{-}NH{-}\underset{\substack{|\\ CH_3}}{CH}CH_3$

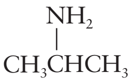
16.7* Draw structural formulas for all amines that have the molecular formula $C_4H_{11}N$. Label each one as a primary, secondary, or tertiary amine.

16.8* Draw structural formulas for the four amines that have the molecular formula C_3H_9N. Label each one as a primary, secondary, or tertiary amine.

The Nomenclature of Amines (Section 16.2)

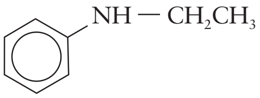
16.9 Give each of the following amines a common name by adding the ending *-amine* to alkyl group names:

a.

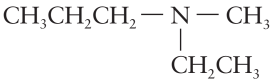


$CH_3\overset{\substack{NH_2\\ |}}{C}HCH_3$

b.



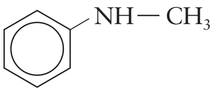
c.



$CH_3CH_2CH_2{-}\underset{\substack{|\\ CH_2CH_3}}{N}{-}CH_3$

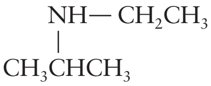
16.10 Give each of the following amines a common name by adding the ending *-amine* to alkyl group names:

a.



b. $CH_3CH_2{-}NH{-}CH_2CH_3$

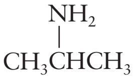
c.



$CH_3\overset{\substack{NH-CH_2CH_3\\ |}}{C}HCH_3$

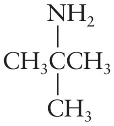
16.11 Give each of the following amines an IUPAC name:

a.



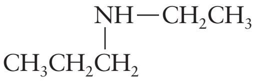
$CH_3\overset{\substack{NH_2\\ |}}{C}HCH_3$

b.



$CH_3\overset{\substack{NH_2\\ |}}{\underset{\substack{|\\ CH_3}}{C}}CH_3$

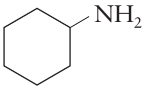
c.



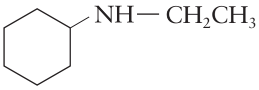
$CH_3CH_2\overset{\substack{NH-CH_2CH_3\\ |}}{CH_2}$

16.12 Give each of the following amines an IUPAC name:

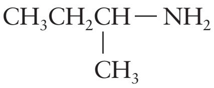
a.



b.



c.

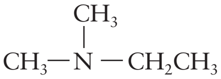


$CH_3CH_2\underset{\substack{|\\ CH_3}}{CH}{-}NH_2$

16.13 Give each of the following amines an IUPAC name:

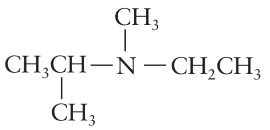
a. $CH_3CH_2{-}NH_2$

b.



$CH_3{-}\overset{\substack{CH_3\\ |}}{N}{-}CH_2CH_3$

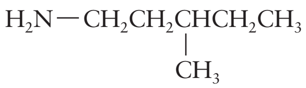
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

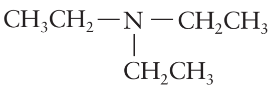
c. 
$\mathrm{CH_3\underset{\displaystyle CH_3}{CH}-\overset{\displaystyle CH_3}{N}-CH_2CH_3}$

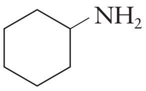
d. $\mathrm{CH_3CH_2CH_2{-}NH{-}CH_2CH_2CH_3}$

16.14 Give each of the following amines an IUPAC name:

a. $\mathrm{CH_3CH_2{-}NH{-}CH_3}$

b. 
$\mathrm{H_2N-CH_2CH_2\underset{\displaystyle CH_3}{CH}CH_2CH_3}$

c. 
$\mathrm{CH_3CH_2-\underset{\displaystyle CH_2CH_3}{N}-CH_2CH_3}$

d. 

16.15 Draw the structural formula for each of the following amines:

a. 3-ethyl-2-pentanamine

b. diethylpropylamine

c. 3-methylcyclohexanamine

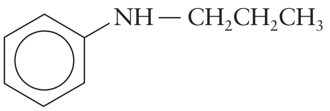
16.16 Draw the structural formula for each of the following amines:

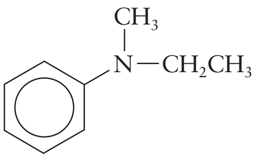
a. 3-chloro-2-pentanamine

b. 3-methyl-2-butanamine

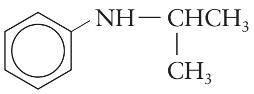
c. ethylamine

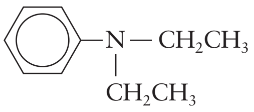
16.17* Name the following aromatic amines as derivatives of aniline:

a. 

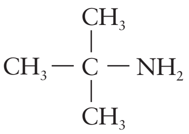
b. 

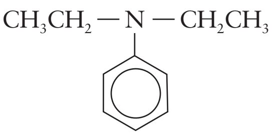
16.18 Name the following aromatic amines as derivatives of aniline:

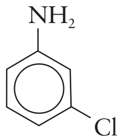
a. 

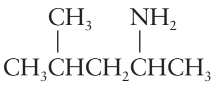
b. 

16.19* Name each of the following amines by one of the methods used in Exercises 16.9, 16.11, and 16.17:

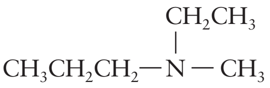
a. 
$\mathrm{CH_3-\underset{\displaystyle CH_3}{\overset{\displaystyle CH_3}{C}}-NH_2}$

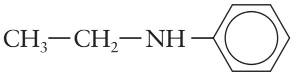
b. 

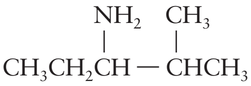
c. 

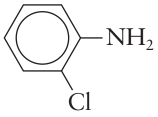
d. 
$\mathrm{CH_3\overset{\displaystyle CH_3}{CH}CH_2\overset{\displaystyle NH_2}{CH}CH_3}$

16.20 Name each of the following amines by one of the methods used in Exercises 16.7, 16.11, and 16.17.

a. 
$\mathrm{CH_3CH_2CH_2-\overset{\displaystyle CH_2CH_3}{N}-CH_3}$

b. 

c. 
$\mathrm{CH_3CH_2\overset{\displaystyle NH_2}{CH}-\overset{\displaystyle CH_3}{CH}CH_3}$

d. 

16.21 Draw the structural formula for each of the following amines:

a. diisopropylamine

b. *p*-ethylaniline

c. 2-methylcyclopentanamine

d. *N*-methyl-3-ethylaniline

16.22 Draw the structural formula for each of the following amines:

a. *N*,*N*-dimethylaniline

b. 3-ethyl-2-hexanamine

c. *N*,*N*-dimethyl-1-butanamine

d. Triethylamine

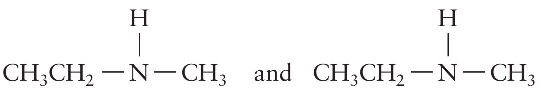
Physical Properties of Amines (Section 16.3)

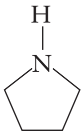
16.23 Explain why all classes of low molecular weight amines are water soluble.

16.24* Why are the boiling points of amines lower than those of corresponding alcohols?

16.25* Why are the boiling points of tertiary amines lower than those of corresponding primary and secondary amines?

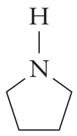
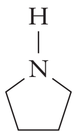
16.26 Draw diagrams similar to **Figure 16.1** to illustrate hydrogen bonding between the following compounds:

a. 
$\mathrm{CH_3CH_2-\overset{\displaystyle H}{N}-CH_3}$ and $\mathrm{CH_3CH_2-\overset{\displaystyle H}{N}-CH_3}$

b.  and $\mathrm{H_2O}$

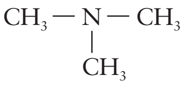
16.27 Draw diagrams similar to **Figure 16.1** to illustrate hydrogen bonding between the following compounds:

a. $CH_3CH_2-NH-CH_3$ and H_2O

b.  and 

16.28 Arrange the following compounds in order of increasing boiling point:

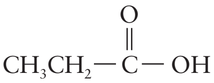
a. $CH_3CH_2CH_2CH_3$

b. 
$CH_3-\underset{\displaystyle CH_3}{\underset{|}{N}}-CH_3$

c. $CH_3CH_2CH_2-OH$

16.29 Arrange the following compounds in order of increasing boiling point:

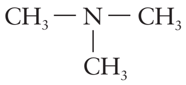
a. $CH_3CH_2CH_2-NH_2$

b. 
$CH_3CH_2-\overset{\displaystyle O}{\overset{\|}{C}}-OH$

c. $CH_3CH{=}CHCH_3$

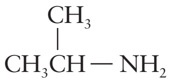
16.30 Arrange the following compounds in order of increasing boiling point:

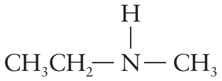
a. $CH_3CH_2CH_2-NH_2$

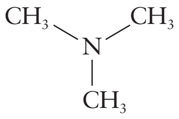
b. 
$CH_3-\underset{\displaystyle CH_3}{\underset{|}{N}}-CH_3$

c. $CH_3CH_2CH_2-OH$

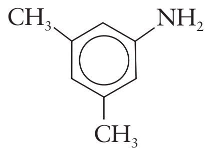
16.31 Arrange the following compounds in the order of increasing boiling point:

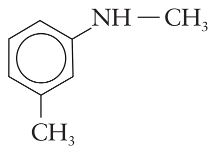
a. 
$CH_3\overset{\displaystyle CH_3}{\overset{|}{C}H}-NH_2$

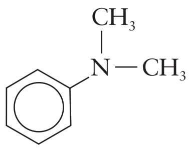
b. 
$CH_3CH_2-\overset{\displaystyle H}{\overset{|}{N}}-CH_3$

c. 

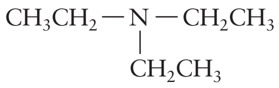
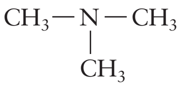
16.32 Arrange the following compounds in order of increasing boiling point:

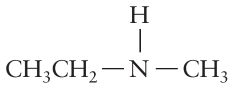
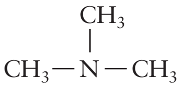
a. 

c. 

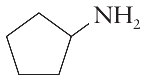
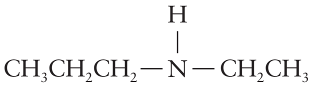
b. 

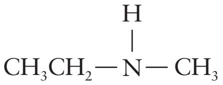
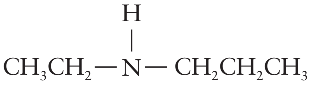
16.33 Identify which amine in the following pairs would be more water soluble. Explain your answer.

a. 
$CH_3CH_2-\underset{\displaystyle CH_2CH_3}{\underset{|}{N}}-CH_2CH_3$
and 
$CH_3-\underset{\displaystyle CH_3}{\underset{|}{N}}-CH_3$

b. 
$CH_3CH_2-\overset{\displaystyle H}{\overset{|}{N}}-CH_3$
and 
$CH_3-\overset{\displaystyle CH_3}{\overset{|}{N}}-CH_3$

16.34 Identify which amine in the following pairs would be more water soluble. Explain your answer.

a. 
and 
$CH_3CH_2CH_2-\overset{\displaystyle H}{\overset{|}{N}}-CH_2CH_3$

b. 
$CH_3CH_2-\overset{\displaystyle H}{\overset{|}{N}}-CH_3$
and 
$CH_3CH_2-\overset{\displaystyle H}{\overset{|}{N}}-CH_2CH_2CH_3$

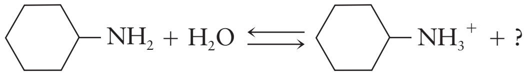
Chemical Properties of Amines (Section 16.4)

16.35 Explain why CH_3-NH_2 is a Brønsted base.

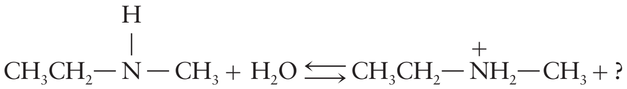
16.36 When diethylamine is dissolved in water, the solution becomes basic. Write an equation to account for this observation.

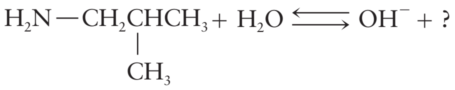
16.37 Draw the structural formula of the missing substance in each of the following reactions:

a. $CH_3-NH-CH_3 + H_2O \rightleftharpoons OH^- + ?$

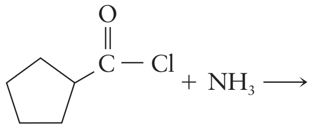
b. 

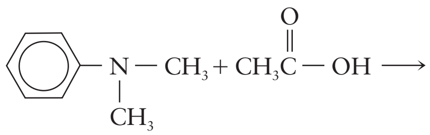
16.38 Draw the structural formula of the missing substance in each of the following reactions:

a. 
$CH_3CH_2-\overset{\displaystyle H}{\overset{|}{N}}-CH_3 + H_2O \rightleftharpoons CH_3CH_2-\overset{+}{N}H_2-CH_3 + ?$

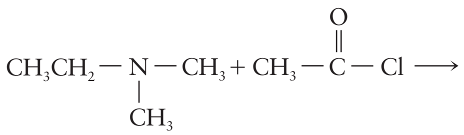
b. 
$H_2N-CH_2\underset{\displaystyle CH_3}{\underset{|}{C}H}CH_3 + H_2O \rightleftharpoons OH^- + ?$

16.39 Complete the following equations. If no reaction occurs, write "no reaction."

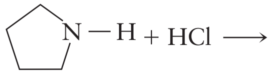
a. 

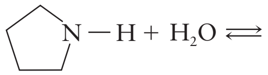
b. 

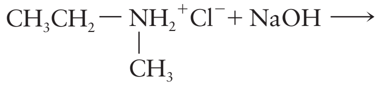
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

c. 

$$\mathrm{CH_3CH_2-\underset{\underset{\displaystyle CH_3}{|}}{N}-CH_3+CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-Cl \longrightarrow}$$

d. 

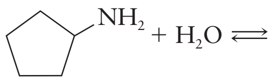
e. 

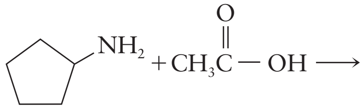
f. 

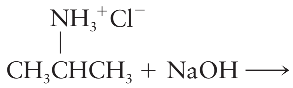
$$\mathrm{CH_3CH_2-\underset{\underset{\displaystyle CH_3}{|}}{NH_2^+}Cl^- + NaOH \longrightarrow}$$

16.40 Complete the following equations. If no reaction occurs, write "no reaction."

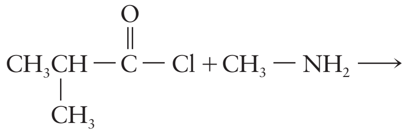
a. $CH_3CH_2CH_2CH_2{-}NH_2 + HCl \rightarrow$

b. 

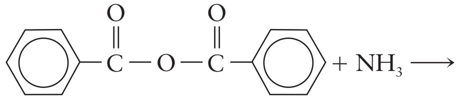
c. 

d. 

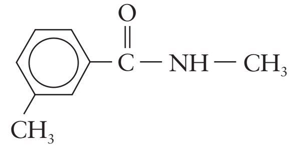
$$\mathrm{CH_3\underset{}{\overset{\overset{\displaystyle NH_3^+Cl^-}{|}}{C}}HCH_3 + NaOH \longrightarrow}$$

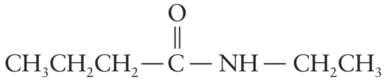
e. 

$$\mathrm{CH_3\underset{\underset{\displaystyle CH_3}{|}}{CH}-\overset{\overset{\displaystyle O}{\|}}{C}-Cl+CH_3-NH_2 \longrightarrow}$$

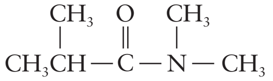
f. 

16.41 Draw the structural formulas for the carboxylic acid chloride molecule used to make each of the following amides:

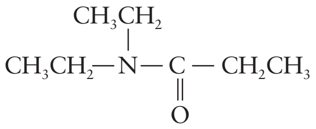
a. 

b. 

$$\mathrm{CH_3CH_2CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-NH-CH_2CH_3}$$

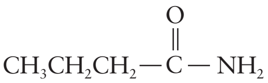
c. 

$$\mathrm{CH_3\overset{\overset{\displaystyle CH_3}{|}}{C}H-\overset{\overset{\displaystyle O}{\|}}{C}-\overset{\overset{\displaystyle CH_3}{|}}{N}-CH_3}$$

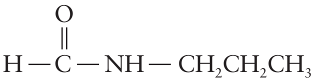
d. 

$$\mathrm{CH_3CH_2-\overset{\overset{\displaystyle CH_3CH_2}{|}}{N}-\underset{\underset{\displaystyle O}{\|}}{C}-CH_2CH_3}$$

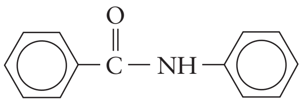
16.42 Draw the structural formulas for the carboxylic acid chloride molecule that is used to make each of the following amides:

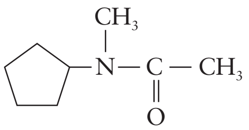
a. 

$$\mathrm{CH_3CH_2CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2}$$

b. 

$$\mathrm{H-\overset{\overset{\displaystyle O}{\|}}{C}-NH-CH_2CH_2CH_3}$$

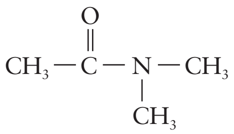
c. 

d. 

16.43 Draw the structural formulas of the carboxylic acid anhydride molecule that was used to make each of the amides in Exercise 16.41.

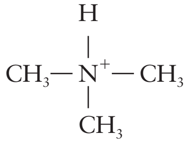
16.44 Draw the structural formulas of the carboxylic acid anhydride molecule that was used to make each of the amides in Exercise 16.42.

16.45 Write equations for two different methods of synthesizing the following amide:

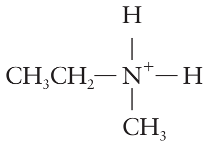


$$\mathrm{CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-\underset{\underset{\displaystyle CH_3}{|}}{N}-CH_3}$$

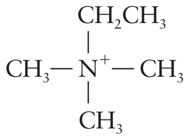
16.46 Identify each of the following as an amine salt or a quaternary ammonium salt. Assume that a negative chloride ion is present in each case.

a. 

$$\mathrm{CH_3-\underset{\underset{\displaystyle CH_3}{|}}{\overset{\overset{\displaystyle H}{|}}{N^+}}-CH_3}$$

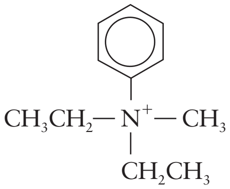
b. 

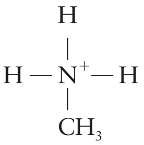
$$\mathrm{CH_3CH_2-\underset{\underset{\displaystyle CH_3}{|}}{\overset{\overset{\displaystyle H}{|}}{N^+}}-H}$$

c. 

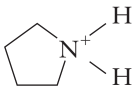
$$\mathrm{CH_3-\underset{\underset{\displaystyle CH_3}{|}}{\overset{\overset{\displaystyle CH_2CH_3}{|}}{N^+}}-CH_3}$$

16.47 Identify each of the following as an amine salt or a quaternary ammonium salt. Assume that a negative chloride ion is present in each case.

a.


b.


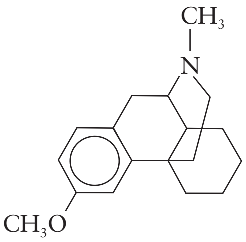
$$H-\underset{\underset{\displaystyle CH_3}{|}}{\overset{\overset{\displaystyle H}{|}}{N^+}}-H$$

c.


16.48 How does the structure of a quaternary ammonium salt differ from the structure of a salt of a tertiary amine?

16.49 Why are amine drugs commonly administered in the form of their salts?

16.50 Write an equation to show how the drug dextromethorphan, a cough suppressant, could be made more water soluble.

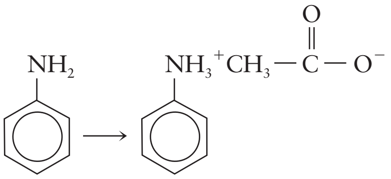


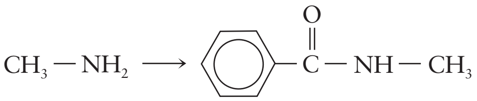
dextromethorphan

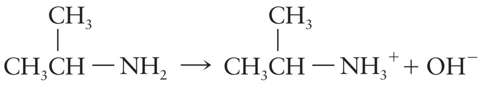
16.51 What types of reactants are needed to produce a polyamide?

16.52 Contrast the reactants needed to produce a polyamide with those needed to produce a polyester.

16.53 Write structures for the chemicals needed to carry out the following conversions:

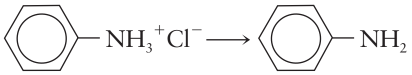
a.


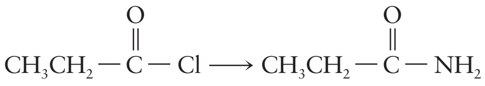
b.


c.


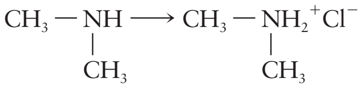
$$CH_3\overset{\overset{\displaystyle CH_3}{|}}{CH}-NH_2 \longrightarrow CH_3\overset{\overset{\displaystyle CH_3}{|}}{CH}-NH_3^+ + OH^-$$

16.54 Write structures for the chemicals needed to carry out the following conversions:

a.


b.


$$CH_3CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-Cl \longrightarrow CH_3CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2$$

c.


$$CH_3-\underset{\underset{\displaystyle CH_3}{|}}{NH} \longrightarrow CH_3-\underset{\underset{\displaystyle CH_3}{|}}{NH_2^+}Cl^-$$

Amines as Neurotransmitters (Section 16.5)

16.55 Describe the general structure of a neuron.

16.56 What term is used to describe the gap between one neuron and the next?

16.57 Name the two amino acids that are starting materials for the synthesis of neurotransmitters.

16.58 Name the two amines often associated with the biochemical theory of mental illness.

16.59 What role do neurotransmitters play in nerve impulse transmission?

16.60 List four neurotransmitters important in the central nervous system.

Other Biologically Important Amines (Section 16.6)

16.61 Why is epinephrine called the fight-or-flight hormone?

16.62 Describe one clinical use of epinephrine.

16.63 What are the physiological effects of amphetamines on the body?

16.64 What is the source of alkaloids?

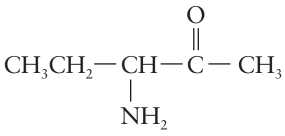
16.65 Why are alkaloids weakly basic?

16.66 Give the name of an alkaloid for the following:

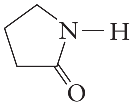
- **a.** Found in cola drinks
- **b.** Used to reduce saliva flow during surgery
- **c.** Present in tobacco
- **d.** A cough suppressant
- **e.** Used to treat malaria
- **f.** An effective painkiller

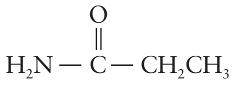
The Nomenclature of Amides (Section 16.7)

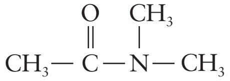
16.67 Identify which of the following compounds are amides:

a.


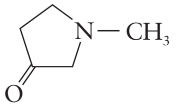
$$CH_3CH_2-\underset{\underset{\displaystyle NH_2}{|}}{CH}-\overset{\overset{\displaystyle O}{\|}}{C}-CH_3$$

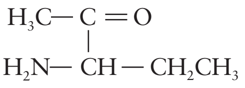
b.


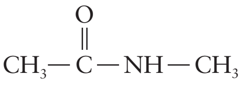
c. 
$H_2N-\overset{O}{\overset{\|}{C}}-CH_2CH_3$

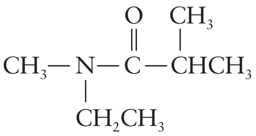
d. 
$CH_3-\overset{O}{\overset{\|}{C}}-\overset{CH_3}{\overset{|}{N}}-CH_3$

16.68 Identify which of the following compounds are amides:

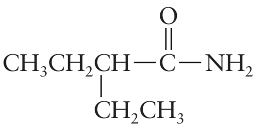
a. 

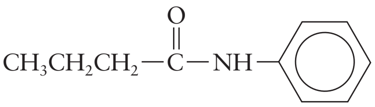
b. 
$H_2N-\overset{\overset{H_3C-C=O}{|}}{CH}-CH_2CH_3$

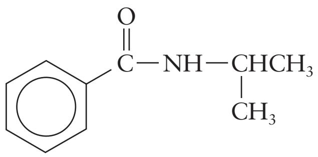
c. 
$CH_3-\overset{O}{\overset{\|}{C}}-NH-CH_3$

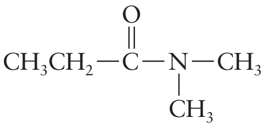
d. 
$CH_3-\underset{\underset{CH_2CH_3}{|}}{N}-\overset{O}{\overset{\|}{C}}-\overset{CH_3}{\overset{|}{C}H}CH_3$

16.69 Assign IUPAC names to the following amides:

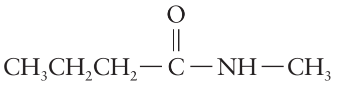
a. 
$CH_3CH_2\underset{\underset{CH_2CH_3}{|}}{CH}-\overset{O}{\overset{\|}{C}}-NH_2$

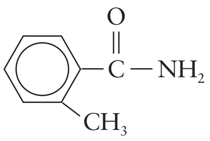
b. 

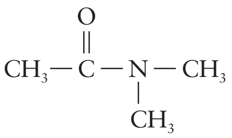
c. 

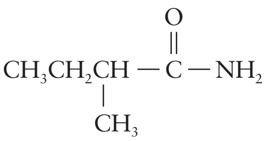
d. 
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-\underset{\underset{CH_3}{|}}{N}-CH_3$

16.70 Assign IUPAC names to the following amides:

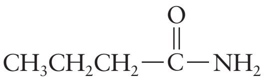
a. 
$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-NH-CH_3$

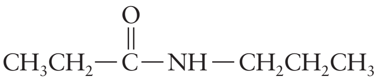
c. 

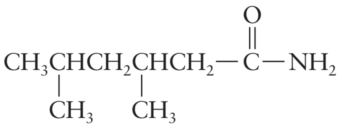
b. 
$CH_3-\overset{O}{\overset{\|}{C}}-\underset{\underset{CH_3}{|}}{N}-CH_3$

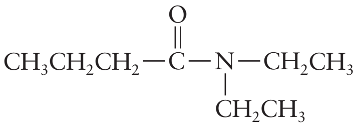
d. 
$CH_3CH_2\underset{\underset{CH_3}{|}}{CH}-\overset{O}{\overset{\|}{C}}-NH_2$

16.71 Assign IUPAC names to the following amides:

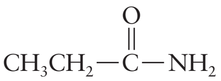
a. 
$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-NH_2$

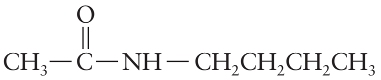
b. 
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-NH-CH_2CH_2CH_3$

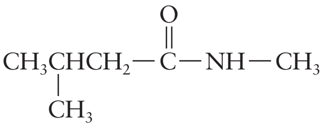
c. 
$CH_3\underset{\underset{CH_3}{|}}{C}HCH_2\underset{\underset{CH_3}{|}}{C}HCH_2-\overset{O}{\overset{\|}{C}}-NH_2$

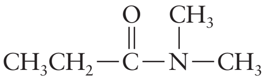
d. 
$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-\underset{\underset{CH_2CH_3}{|}}{N}-CH_2CH_3$

16.72 Assign IUPAC names to the following amides:

a. 
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-NH_2$

b. 
$CH_3-\overset{O}{\overset{\|}{C}}-NH-CH_2CH_2CH_2CH_3$

c. 
$CH_3\underset{\underset{CH_3}{|}}{C}HCH_2-\overset{O}{\overset{\|}{C}}-NH-CH_3$

d. 
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-\overset{CH_3}{\overset{|}{N}}-CH_3$

16.73 Draw structural formulas for the following amides:

a. benzamide
b. *N*-methylethanamide
c. *N*-methyl-3-phenylbutanamide

16.74 Draw structural formulas for the following amides:

a. butanamide
b. *N*-ethylbenzamide
c. *N*,*N*-dimethylpropanamide

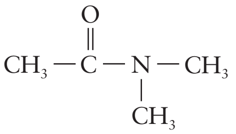
Physical Properties of Amides (Section 16.8)

16.75 Explain why low-molecular-weight amides are relatively water soluble.

16.76 Would you expect *N*-ethylpropanamide or *N*,*N*-dimethylpropanamide to have the higher boiling point? Explain your answer.

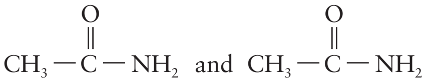
16.77 Draw diagrams similar to those in **Figure 16.1** to illustrate hydrogen bonding between the following molecules:

a.



$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-\underset{\underset{\displaystyle CH_3}{|}}{N}-CH_3 \text{ and } H_2O$$

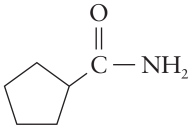
b.



$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2 \text{ and } CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2$$

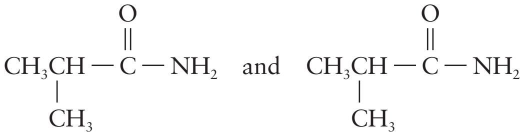
16.78 Draw diagrams similar to those in **Figure 16.1** to illustrate hydrogen bonding between the following molecules:

a.



and H_2O

b.



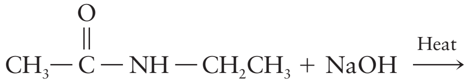
$$CH_3\underset{\underset{\displaystyle CH_3}{|}}{CH}-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2 \text{ and } CH_3\underset{\underset{\displaystyle CH_3}{|}}{CH}-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2$$

16.79* Explain why the boiling points of disubstituted amides are often lower than those of unsubstituted amides.

Chemical Properties of Amides (Section 16.9)

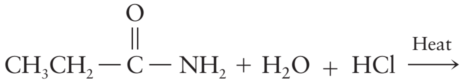
16.80 Complete the following reactions:

a.



$$CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-NH-CH_2CH_3 + NaOH \xrightarrow{\text{Heat}}$$

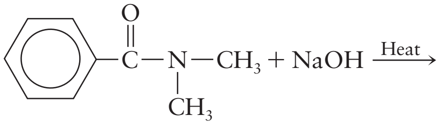
b.



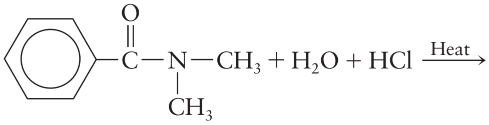
$$CH_3CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2 + H_2O + HCl \xrightarrow{\text{Heat}}$$

16.81 Complete the following reactions:

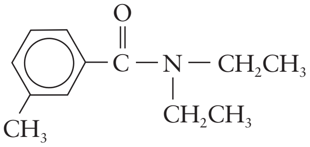
a.



b.

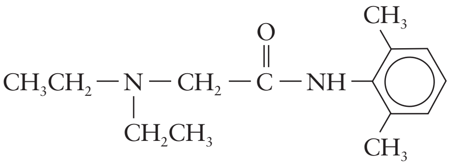


16.82 One of the most successful mosquito repellents has the following structure and name. What are the products of the basic hydrolysis of *N,N*-diethyl-*m*-toluamide?



N,N-diethyl-*m*-toluamide

16.83 What are the products of the acid hydrolysis of the local anesthetic lidocaine?



lidocaine (Xylocaine)

Additional Exercises

16.84 The following molecular formulas represent saturated amine compounds or unsaturated amine compounds that contain C═C bonds. Determine whether each compound is saturated and, if not, how many C═C bonds are present.

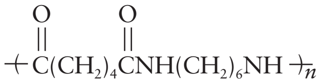
a. $C_4H_{11}N$

b. $C_5H_{12}N_2$

c. C_4H_7N

16.85 16.50 mL of 0.100 M HCl was needed to titrate 0.216 g of an unknown amine to a neutral pH endpoint. What is the molecular weight of the amine? Assume the compound only contains one nitrogen atom and there are no other reactive groups present.

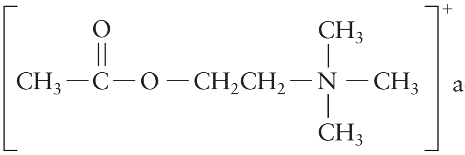
16.86 What products would result from the hydrolysis with NaOH of nylon 66 (polymer shown here)?



$$\left[\overset{\overset{\displaystyle O}{\|}}{C}(CH_2)_4\overset{\overset{\displaystyle O}{\|}}{C}NH(CH_2)_6NH\right]_n$$

16.87 Finely ground plant material can be treated with a base to aid in the extraction of alkaloids present in the tissue. Explain why.

16.88 After a nerve impulse occurs, excess acetylcholine cation molecules in the synapse are hydrolyzed in about 10^{-6} seconds by the enzyme cholinesterase. What products are formed? *Hint:* Identify the functional group that can undergo hydrolysis (upon the addition of water).



$$\left[CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-O-CH_2CH_2-\underset{\underset{\displaystyle CH_3}{|}}{\overset{\overset{\displaystyle CH_3}{|}}{N}}-CH_3\right]^+$$

acetylcholine cation

Chemistry for Thought

16.89 Why might it be more practical for chemical suppliers to ship amines as amine salts?

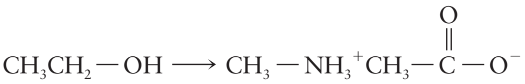
16.90 Give structural formulas for the four carbon diamine and the four carbon diacid chloride that would react to form nylon.

16.91 Why might it be dangerous on a camping trip to prepare a salad using an unknown plant?

16.92 One of the active ingredients in Triaminic® cold syrup is listed as chlorpheniramine maleate. What does the word *maleate* indicate about the structure of this active ingredient?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

16.93 Write reactions to show how the following conversion can be achieved. An amine reagent is required, and reactions from earlier chapters are necessary.



$$CH_3CH_2-OH \longrightarrow CH_3-NH_3^{+}CH_3-\overset{\overset{O}{\|}}{C}-O^{-}$$

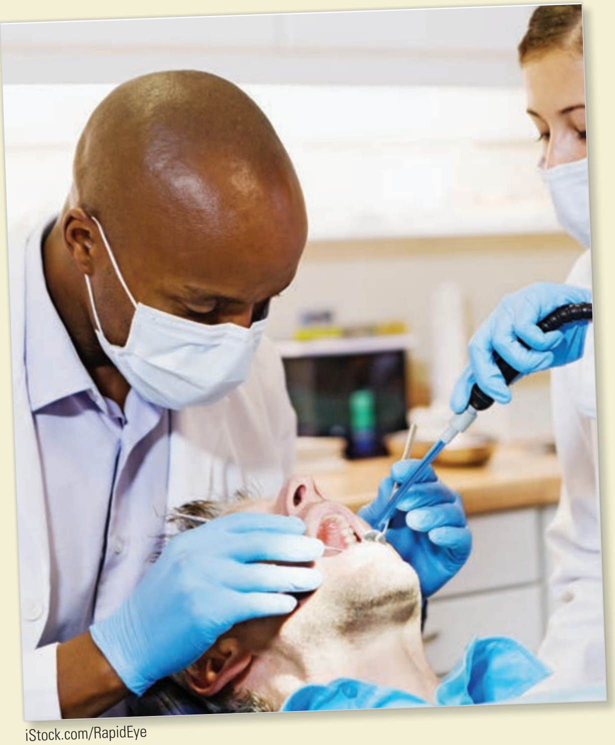
16.94 Several OTC products are available that contain amine salts. Sometimes the active ingredients are given common names ending in hydrochloride. What acid do you think is used to prepare an amine hydrochloride salt?

16.95 In **Section 21.1**, several components of nucleic acids, DNA and RNA, are identified as “bases.” What molecular feature of these substances might explain why they are referred to as bases?

16.96 The hydrolysis of amides requires rather vigorous conditions of strong acid or base and heat. What technique might be employed to achieve hydrolysis under milder conditions?

16.97 Alkaloids can be extracted from plant tissues using dilute hydrochloric acid. Why does the use of acid enhance their water solubility?

17 Carbohydrates



iStock.com/RapidEye

Health Career Focus

DENTAL ASSISTANT

I love working with children, and I get that opportunity in my work at the dentist's office. In college, I made a brochure for my chemistry course that also earned credit in my dental program. It showed different foods and how they affect the teeth. I still use that at work to teach kids about dental health.

Most children know that sugar is bad for their teeth, but many are surprised to learn that enzymes in the mouth turn starches into sugar. So, carbohydrate-rich foods like crackers and even potatoes can be as damaging as candy.

When I give a child their gift bag—with a toothbrush, floss, and toothpaste—at the end of the appointment, I think about the difference I'm making in the health of a child. It's rewarding to know that my work is important.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Describe the four major functions of carbohydrates in living organisms. **(Section 17.1)**
2. Classify carbohydrates as monosaccharides, disaccharides, or polysaccharides. **(Section 17.1)**
3. Identify molecules possessing chiral carbon atoms. **(Section 17.2)**
4. Use Fischer projections to represent D and L compounds. **(Section 17.3)**
5. Classify monosaccharides as aldoses or ketoses, and classify them according to the number of carbon atoms they contain. **(Section 17.4)**
6. Write reactions for monosaccharide oxidation and glycoside formation. **(Section 17.5)**
7. Describe uses for important monosaccharides. **(Section 17.6)**
8. Draw the structures and list sources and uses for important disaccharides. **(Section 17.7)**
9. Write reactions for the hydrolysis of disaccharides. **(Section 17.7)**
10. Describe the structures and list sources and uses for important polysaccharides. **(Section 17.8)**

CARBOHYDRATES ARE COMPOUNDS of tremendous biological and commercial importance. Widely distributed in nature, they include such familiar substances as cellulose, table sugar, and starch (see **Figure 17.1**). Carbohydrates have four important functions in living organisms:

- To provide energy through their oxidation.
- To supply carbon for the synthesis of cell components.
- To serve as a stored form of chemical energy.
- To form a part of the structural elements of some cells and tissues.

Billion Photos/Shutterstock.com

FIGURE 17.1 Foods such as pasta, bread, and rice are high in carbohydrates, which supply energy for the body and supply carbon for the synthesis of cell components.

With carbohydrates, we begin our study of **biomolecules**, substances closely associated with living organisms. All life processes, as far as we know, involve carbohydrates and other biomolecules, including lipids, proteins, and nucleic acids. Biomolecules are organic because they are compounds of carbon, but they are also a starting point for **biochemistry**, the chemistry of living organisms. Thus, these chapters on biomolecules represent an overlap of two areas of chemistry: organic and biochemistry.

biomolecule A general term referring to organic compounds essential to life.

biochemistry A study of the compounds and processes associated with living organisms.

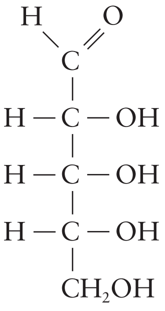
17.1 Classes of Carbohydrates

Learning Objective 1 Describe the four major functions of carbohydrates in living organisms.

Learning Objective 2 Classify carbohydrates as monosaccharides, disaccharides, or polysaccharides.

The name *carbohydrate* comes from an early observation that heating these compounds produced water and a black residue of carbon, which was incorrectly interpreted to mean that they were hydrates of carbon.

The most striking chemical characteristic of carbohydrates is the large number of functional groups they have. For example, ribose has a functional group on every carbon atom of its five-carbon chain:



ribose

In addition to —OH groups, most carbohydrates have as part of their molecular structure a carbonyl group—either an aldehyde (sometimes shown as —CHO) or a ketone functional

carbohydrate A polyhydroxy aldehyde or ketone, or substance that yields such compounds on hydrolysis.

monosaccharide A simple carbohydrate most commonly consisting of three to six carbon atoms.

disaccharide A carbohydrate formed by the combination of two monosaccharide units.

polysaccharide A carbohydrate formed by the combination of many monosaccharide units.

group. This is the origin of the modern definition: **Carbohydrates** are polyhydroxy aldehydes or ketones, or substances that yield such compounds on hydrolysis.

Carbohydrates can be classified according to the size of the molecules. **Monosaccharides** consist of a single polyhydroxy aldehyde or ketone unit. **Disaccharides** are carbohydrates composed of two monosaccharide units linked together chemically. Oligosaccharides (less common and of minor importance) contain three to ten units. **Polysaccharides** consist of very long chains of linked monosaccharide units (see **Figure 17.2**).

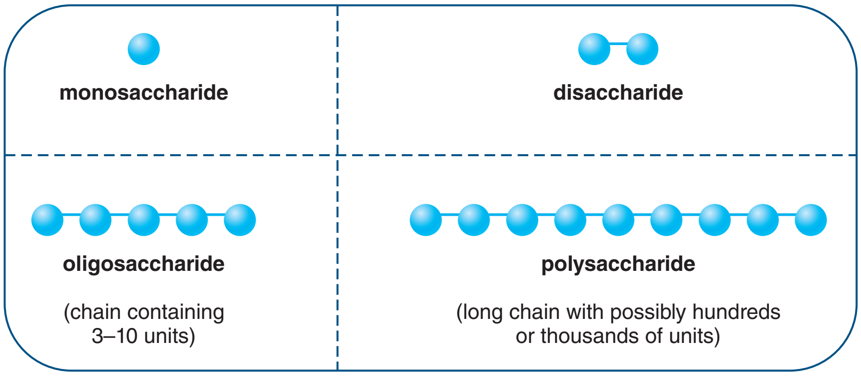

monosaccharide
disaccharide
oligosaccharide
(chain containing 3–10 units)
polysaccharide
(long chain with possibly hundreds or thousands of units)

FIGURE 17.2 Carbohydrate classification.

17.2 The Stereochemistry of Carbohydrates

Learning Objective 3 Identify molecules possessing chiral carbon atoms.

enantiomers Stereoisomers that are mirror images.

Glyceraldehyde, the simplest carbohydrate, exhibits a fascinating stereoisomerism shown by many organic compounds but especially characteristic of carbohydrates and many other natural substances. Glyceraldehyde can exist in two isomeric forms that are mirror images of each other (see **Figure 17.3**). Mirror-image isomers, called **enantiomers**, have the same molecular and structural formulas but different spatial arrangements of their atoms. No amount of rotation can convert one of these structures into the other. The molecules can be compared to right and left hands, which are also mirror images of each other (see **Figure 17.4**). Test this yourself. Put your right hand up to a mirror, and verify that its mirror image is the same as the direct image of your left hand.

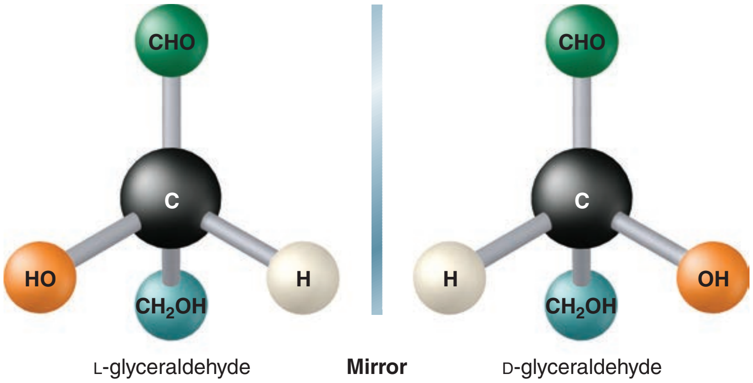


FIGURE 17.3 Enantiomers of glyceraldehyde. The designations L and D are discussed in **Section 17.3**.

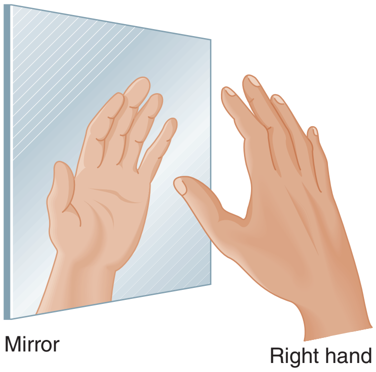


FIGURE 17.4 The reflection of a right hand is a left hand.

Compare your right hand with the right hand of a friend. Note that they can be overlapped or superimposed (see **Figure 17.5**). Now try to rotate or twist your right and left hands so that one is superimposed on the other and turned the exact same way. It cannot be done. Even if you place your hands palm-to-palm so the profiles superimpose, the nails are on the wrong sides. The same thing happens when you try to put a left-hand glove on your right hand.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

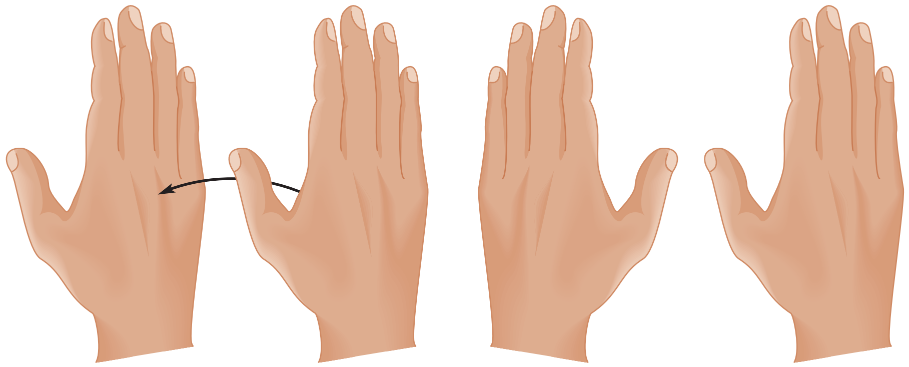


FIGURE 17.5 Two right hands can be superimposed; a right hand and a left hand cannot.

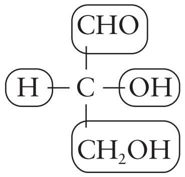
When an object cannot be superimposed on its mirror image, the object is said to be **chiral**. Thus, a hand, a glove, and a shoe are chiral objects; they cannot be superimposed on their mirror images. However, a drinking glass, a sphere, and a cube are achiral objects because they can be superimposed on their mirror images.

chiral A descriptive term for compounds or objects that cannot be superimposed on their mirror image.

Many molecules in addition to glyceraldehyde are chiral, but fortunately it is not necessary to try to superimpose them on their mirror images in order to determine whether or not they are chiral. An organic molecule that contains a carbon atom attached to four different groups will be chiral and thus will have two non-superimposable mirror images. A carbon atom with four different groups attached is called a **chiral carbon**.

chiral carbon A carbon atom with four different groups attached.

The center carbon of glyceraldehyde



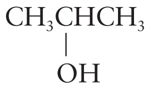
$$\begin{array}{c} \boxed{\mathrm{CHO}} \\ | \\ \boxed{\mathrm{H}}-\mathrm{C}-\boxed{\mathrm{OH}} \\ | \\ \boxed{\mathrm{CH_2OH}} \end{array}$$

is chiral because it is attached to CHO, H, OH, and CH_2OH groups. Like your hands, the two enantiomers of glyceraldehyde are nonsuperimposable mirror images. No matter how hard we try, there is no way, short of breaking bonds, to superimpose the four groups so that they coincide.

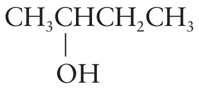
Because the presence of a single chiral carbon atom gives rise to stereoisomerism, it is important to be able to recognize one when you see it. It is really not difficult. If a carbon atom is connected to four different groups, no matter how slight the differences, it is a chiral carbon. If any two groups are identical, it is not a chiral carbon.

Example 17.1 Identifying Chiral Carbons

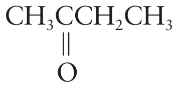
Which of the following compounds contain a chiral carbon?

a. 

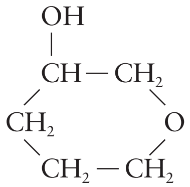
$$\mathrm{CH_3\underset{\underset{\textstyle OH}{|}}{C}HCH_3}$$

b. 

$$\mathrm{CH_3\underset{\underset{\textstyle OH}{|}}{C}HCH_2CH_3}$$

c. 

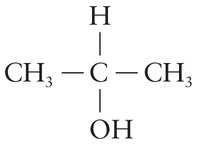
$$\mathrm{CH_3\underset{\underset{\textstyle O}{\|}}{C}CH_2CH_3}$$

d. 

Solution

It may help to draw the structures in a more complete form.

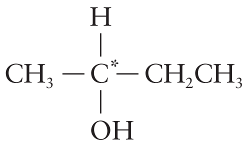
a. The central carbon atom has one H, one OH, but two CH_3 groups attached. It is not chiral. Neither of the other two carbons has four different groups.



$$\begin{array}{c} \mathrm{H} \\ | \\ \mathrm{CH_3-C-CH_3} \\ | \\ \mathrm{OH} \end{array}$$

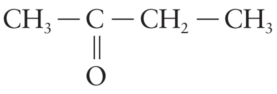
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

b. The central carbon atom has one H, one OH, one CH_3, and one CH_2CH_3 group attached. Both CH_3 and CH_2CH_3 are bonded to the central carbon atom through a carbon atom. However, when analyzing for chiral carbons, we look at the entire collection of atoms in a group and not just at the four atoms directly bonded. Thus, CH_3 and CH_2CH_3 groups are different (as are H and OH), so the central carbon (identified by an asterisk) is chiral. None of the other carbons are chiral.



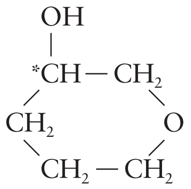
$$\begin{array}{c} \text{H} \\ | \\ \text{CH}_3-\text{C}^{*}-\text{CH}_2\text{CH}_3 \\ | \\ \text{OH} \end{array}$$

c. The carbonyl carbon is attached to only three groups, so it is not chiral, even though the three groups are different. None of the other carbons have four different groups attached.



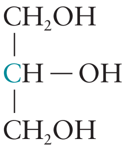
$$\text{CH}_3-\underset{\text{O}}{\underset{\|}{\text{C}}}-\text{CH}_2-\text{CH}_3$$

d. The rules are no different for carbons in rings. There is a chiral carbon marked with an asterisk. H and OH are two of the groups. As we proceed around the ring, —CH_2—O— (the third group) is encountered in the clockwise direction and —CH_2—CH_2— (the fourth group) in the counterclockwise direction.



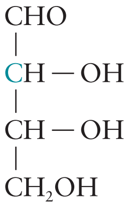
✔ LEARNING CHECK 17.1 Which of the carbon atoms shown in color is chiral?

a.



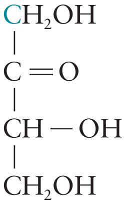
$$\begin{array}{l} \text{CH}_2\text{OH} \\ | \\ \text{CH}-\text{OH} \\ | \\ \text{CH}_2\text{OH} \end{array}$$

b.



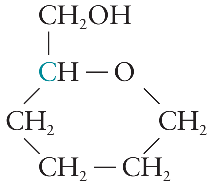
$$\begin{array}{l} \text{CHO} \\ | \\ \text{CH}-\text{OH} \\ | \\ \text{CH}-\text{OH} \\ | \\ \text{CH}_2\text{OH} \end{array}$$

c.

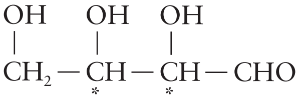


$$\begin{array}{l} \text{CH}_2\text{OH} \\ | \\ \text{C}=\text{O} \\ | \\ \text{CH}-\text{OH} \\ | \\ \text{CH}_2\text{OH} \end{array}$$

d.



Organic molecules (and especially carbohydrates) may contain more than one chiral carbon. Erythrose, for example, has two chiral carbon atoms:



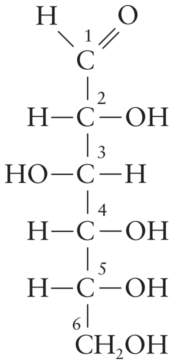
$$\overset{\text{OH}}{\overset{|}{\text{CH}_2}}-\underset{*}{\overset{\text{OH}}{\overset{|}{\text{CH}}}}-\underset{*}{\overset{\text{OH}}{\overset{|}{\text{CH}}}}-\text{CHO}$$

erythrose

Example 17.2 More Identifying Chiral Carbons

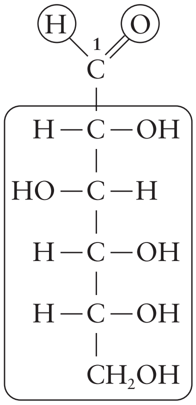
Glucose is present in the blood; the normal range after eating is 135 to 140 mg/dL.

Identify the chiral carbons in glucose:

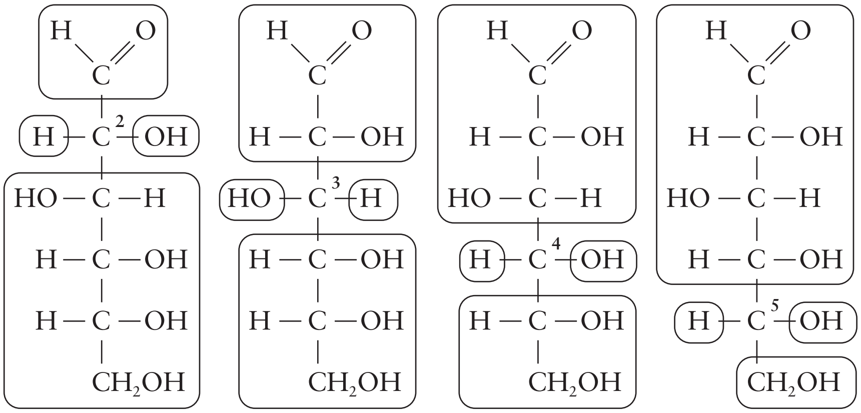


Solution

Carbon number 1 is not chiral, because it has only three groups attached to it:



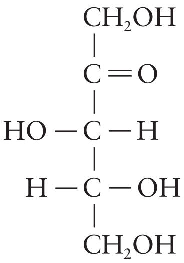
Carbon atoms 2, 3, 4, and 5 are chiral because they each have four different groups attached:



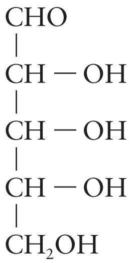
Carbon number 6 is not chiral because two of the four attached groups are the same.

✔ LEARNING CHECK 17.2 Identify the chiral carbon atoms in the following:

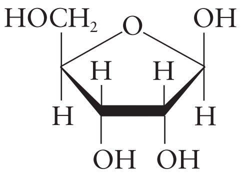
a.



b.



c.



Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

When a molecule contains more than one chiral carbon, the possibility exists for two arrangements of attached groups at each chiral carbon atom. Thus, nearly all molecules having two chiral carbon atoms exist as two pairs of enantiomers, for a total of four stereoisomers. In a similar manner, when there are three chiral carbons present, there are eight stereoisomers (four pairs of enantiomers). The general formula is

$$\text{Maximum number of possible stereoisomers} = 2^n$$

where n is the number of chiral carbon atoms.

Example 17.3 Determining Number of Stereoisomers

How many stereoisomers are possible for a molecule that contains four chiral carbons such as galactose, a component of lactose, or milk sugar?

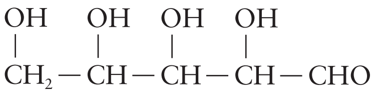
Solution

Stereoisomers $= 2^n$

$$n = 4 \text{ chiral carbons}$$

$$2^4 = 2 \times 2 \times 2 \times 2 = 16$$

✔ **LEARNING CHECK 17.3** How many stereoisomers are possible for the following?



$$\underset{\text{OH}}{\overset{|}{\text{CH}_2}}\!\!-\text{CH}(\text{OH})-\text{CH}(\text{OH})-\text{CH}(\text{OH})-\text{CHO}$$

17.3 Fischer Projections

Learning Objective 4 Use Fischer projections to represent D and L compounds.

It is time-consuming to draw molecules in the three-dimensional shapes shown for the two enantiomers of glyceraldehyde in **Figure 17.3**, but there is a way to represent these mirror images in two dimensions. Emil Fischer, a German chemist known for pioneering work in carbohydrate chemistry, introduced a method late in the 19th century. His two-dimensional structures, called **Fischer projections**, are illustrated in **Figure 17.6** for glyceraldehyde.

Fischer projection A method of depicting three-dimensional shapes for chiral molecules.

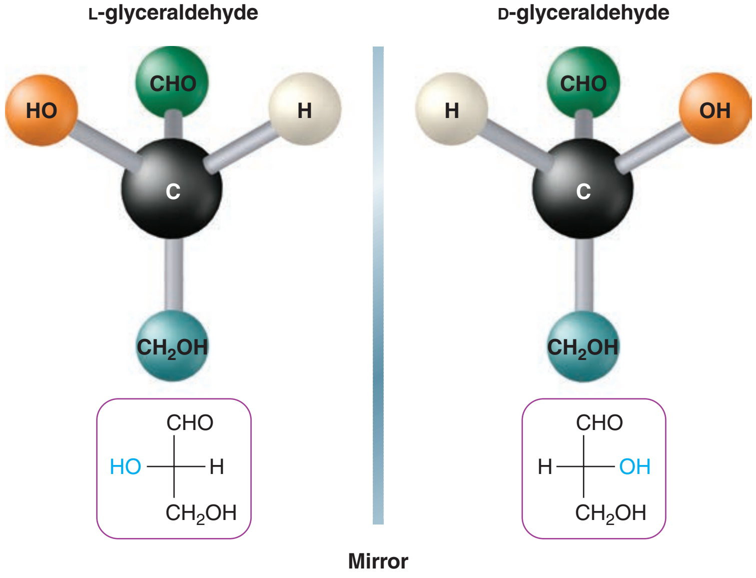


FIGURE 17.6 Ball-and-stick models (top) and Fischer projections (bottom) of the two enantiomers of glyceraldehyde.

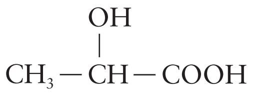
In Fischer projections, the chiral carbon is represented by the intersection of two lines. If the compound is a carbohydrate, the carbonyl group is placed at or near the top. The molecule is also positioned so that the two bonds coming toward you out of the plane of the paper are drawn horizontally in the Fischer projection. The two bonds projecting away from you into the plane of the paper are drawn vertically. Thus, when you see a Fischer projection, you must realize that the molecule has a three-dimensional shape with horizontal bonds coming toward you and vertical bonds going away from you.

Fischer designated the two enantiomers of glyceraldehyde as L and D compounds. Using this system, we can represent the isomers of similar compounds by the direction of bonds about the chiral carbon. A small capital L is used to indicate that an —OH group (or another functional group) is on the left of the chiral carbon when the carbonyl is at the top. A small capital D means the —OH is on the right of the chiral carbon.

Example 17.4 Drawing Fischer Projections

Lactic acid is present in sour milk; alanine is an amino acid, a building block of proteins. Draw Fischer projections for the D and L forms of the following:

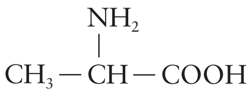
a.



$$CH_3-\overset{\overset{\large OH}{|}}{C}H-COOH$$

lactic acid

b.

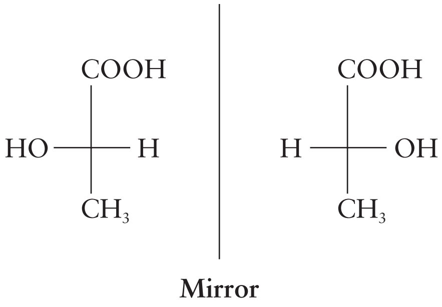


$$CH_3-\overset{\overset{\large NH_2}{|}}{C}H-COOH$$

alanine

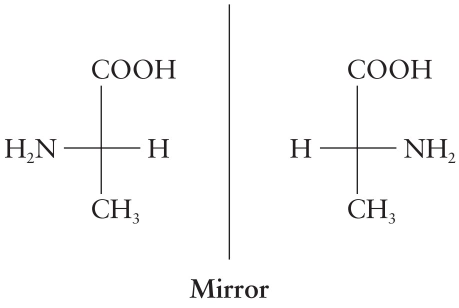
Solution

a. The second carbon of lactic acid is chiral, with four different groups attached: H, OH, CH_3, and COOH. The chiral carbon is placed at the intersection of two lines. Lactic acid is not an aldehyde, but it does contain a carbon–oxygen double bond (in the carboxyl group). This carboxyl group is placed at the top of the vertical line. The direction of the —OH groups on the chiral carbons determines the D and L notations:



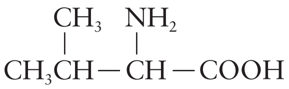
L-lactic acid D-lactic acid

b. Similarly, the amino acid alanine has a chiral carbon and a carboxyl group. The direction of the —NH_2 group determines D and L notations:



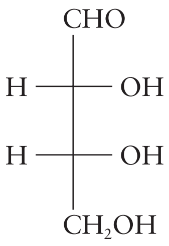
L-alanine D-alanine

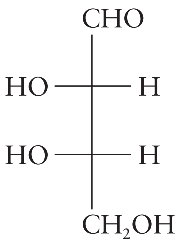
✔ LEARNING CHECK 17.4 Draw Fischer projections for the D and L forms of the following:

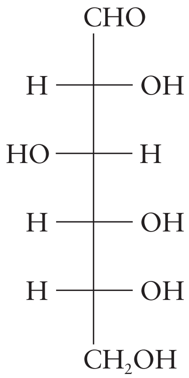


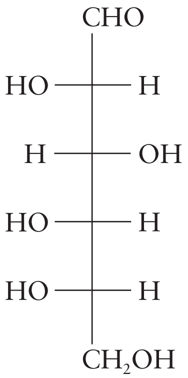
$$CH_3\overset{\overset{\large CH_3}{|}}{C}H-\overset{\overset{\large NH_2}{|}}{C}H-COOH$$

The existence of more than one chiral carbon in a carbohydrate molecule could lead to confusion of D and L designations. This is avoided by focusing on the hydroxy group attached to the chiral carbon farthest from the carbonyl group. By convention, the D family of compounds is that in which this hydroxy group projects to the right when the carbonyl is "up." In the L family of compounds, it projects to the left:


D-erythrose


L-erythrose

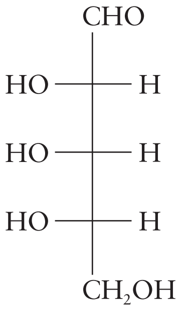

D-glucose


L-glucose

Notice that D and L compounds are mirror images of each other (enantiomers).

Example 17.5 Identifying D and L Isomers

Ribose is a component of ribonucleic acid (RNA), which plays a central role in protein synthesis. Identify the following ribose structure as D or L.

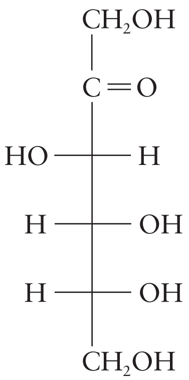


Solution

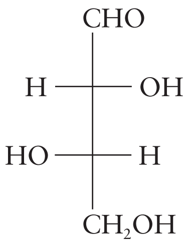
CHO is an abbreviation of the aldehyde group. The intersections of lines represent chiral carbon atoms. Focus on the hydroxy group attached to the chiral carbon farthest from the carbonyl group (aldehyde). The hydroxy group is pointing to the left, so this is L-ribose.

✔ LEARNING CHECK 17.5 Identify each structure as D or L:

a.



b.



Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The physical properties of the two compounds that make up a pair of D and L isomers (enantiomers) are generally the same. The only exception is the way solutions of the two compounds affect polarized light that is passed through them. Light is polarized by passing it through a special polarizing lens, such as those found in polarized sunglasses. When polarized light is passed through a solution of one enantiomer, the plane of polarization of the light is rotated to either the right or the left when viewed by looking toward the source of the light (see **Figure 17.7**). The enantiomer that rotates it to the left is called the **levorotatory** (to the left) or (−) enantiomer. The one that rotates it to the right is the **dextrorotatory** (to the right) or (+) enantiomer.

levorotatory Rotates plane-polarized light to the left.

dextrorotatory Rotates plane-polarized light to the right.

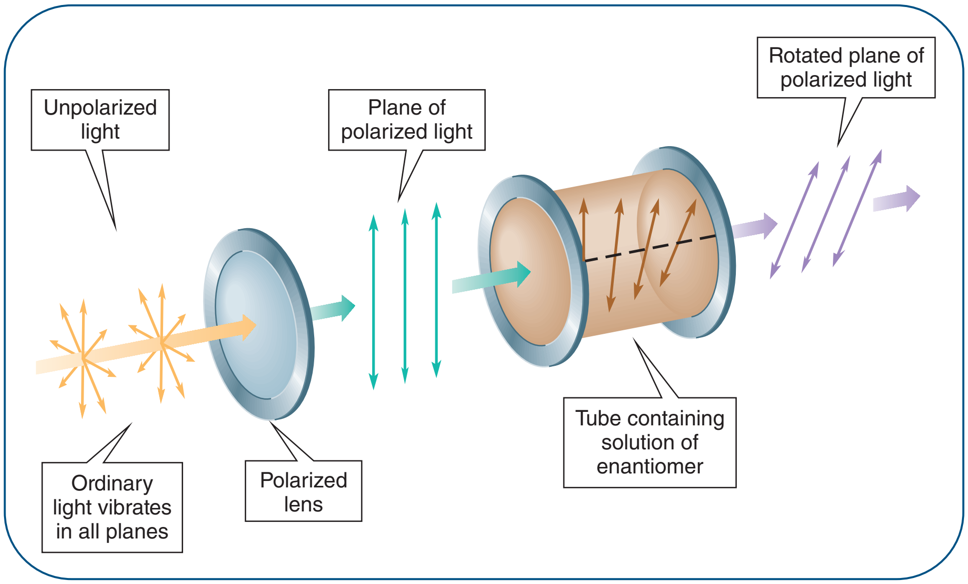

Unpolarized light
Plane of polarized light
Rotated plane of polarized light
Ordinary light vibrates in all planes
Polarized lens
Tube containing solution of enantiomer

FIGURE 17.7 The rotation of plane-polarized light by the solution of an enantiomer.

The D and L designations do not represent the words *dextrorotatory* and *levorotatory* but only the spatial relationships of a Fischer projection. Thus, for example, some D compounds rotate polarized light to the right (dextrorotatory), and some rotate it to the left (levorotatory). The spatial relationships D and L and the rotation of polarized light are entirely different concepts and should not be confused with each other.

The property of rotating the plane of polarized light is called optical activity, and molecules with this property are said to be **optically active**. Measurements of optical activity are useful for differentiating between enantiomers.

optically active molecule A molecule that rotates the plane of polarized light.

Why is it so important to be able to describe stereoisomerism and recognize it in molecules? The reason stems from the fact that living organisms, both plant and animal, consist largely of chiral substances. Most of the compounds in natural systems—including biomolecules such as carbohydrates and amino acids—are chiral. Although these molecules can in principle exist as a mixture of stereoisomers, quite often only one stereoisomer is found in nature (see **Figure 17.8**).

In some instances, two enantiomers are found in nature, but they are not found together in the same biological system. For example, lactic acid occurs naturally in both forms. The L-lactic acid is found in living muscle, whereas the D-lactic acid is present in sour milk. When we realize that only one enantiomer is found in a given biological system, it is not too surprising to find that the system can usually use or assimilate only one enantiomer. Humans utilize the D-isomers of monosaccharides and are unable to metabolize the L-isomers. The D form of glucose tastes sweet, is nutritious, and is an important component of our diets. The L-isomer, on the other hand, is tasteless, and the body cannot use it. Yeast can ferment only D-glucose to produce alcohol, and most animals are able to utilize only L-amino acids in the synthesis of proteins.

lpjp/Shutterstock.com

FIGURE 17.8 The pleasant natural flavor of spearmint is due to the L-enantiomer of carvone, a cyclic ketone.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

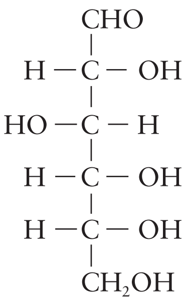
17.4 Monosaccharides

Learning Objective 5 Classify monosaccharides as aldoses or ketoses, and classify them according to the number of carbon atoms they contain.

TABLE 17.1 Monosaccharide Classification Based on the Number of Carbons in Their Chains

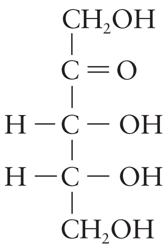
Number of Carbon Atoms	Sugar Class
3	Triose
4	Tetrose
5	Pentose
6	Hexose

The simplest carbohydrates are the monosaccharides, consisting of a single polyhydroxy aldehyde or ketone unit. Monosaccharides are further classified according to the number of carbon atoms they contain (see **Table 17.1**). Thus, simple sugars containing three, four, five, and six carbon atoms are called, respectively, trioses, tetroses, pentoses, and hexoses. The presence of an aldehyde group in a monosaccharide is indicated by the prefix *aldo-*. Similarly, a ketone group is denoted by the prefix *keto-*. Thus, glucose is an aldohexose, and ribulose is a ketopentose:



$$\begin{array}{rcl} & \text{CHO} & \\ & | & \\ \text{H}- & \text{C} & -\text{OH} \\ & | & \\ \text{HO}- & \text{C} & -\text{H} \\ & | & \\ \text{H}- & \text{C} & -\text{OH} \\ & | & \\ \text{H}- & \text{C} & -\text{OH} \\ & | & \\ & \text{CH}_2\text{OH} & \end{array}$$

glucose, an aldohexose

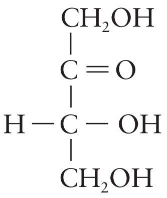


$$\begin{array}{rcl} & \text{CH}_2\text{OH} & \\ & | & \\ & \text{C}=\text{O} & \\ & | & \\ \text{H}- & \text{C} & -\text{OH} \\ & | & \\ \text{H}- & \text{C} & -\text{OH} \\ & | & \\ & \text{CH}_2\text{OH} & \end{array}$$

ribulose, a ketopentose

Example 17.6 Classifying Monosaccharides

Erythrulose (see **Figure 17.9**) is a natural sugar present in red berries such as raspberries. Classify erythrulose by combining the aldehyde–ketone designation with terminology indicating the number of carbon atoms.



$$\begin{array}{rcl} & \text{CH}_2\text{OH} & \\ & | & \\ & \text{C}=\text{O} & \\ & | & \\ \text{H}- & \text{C} & -\text{OH} \\ & | & \\ & \text{CH}_2\text{OH} & \end{array}$$

Solution

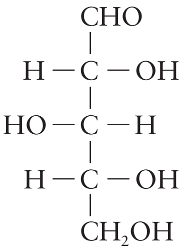
Erythrulose has four carbons (tetrose) and is a ketone (ketose), which makes it a ketotetrose.

Irina Bg/Shutterstock.com

FIGURE 17.9 Erythrulose is a monosaccharide used in many self-tanning products because of its natural ability to dye the skin.

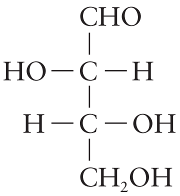
✔ **LEARNING CHECK 17.6** Classify each of the following monosaccharides by combining the aldehyde–ketone designation with terminology indicating the number of carbon atoms:

a.



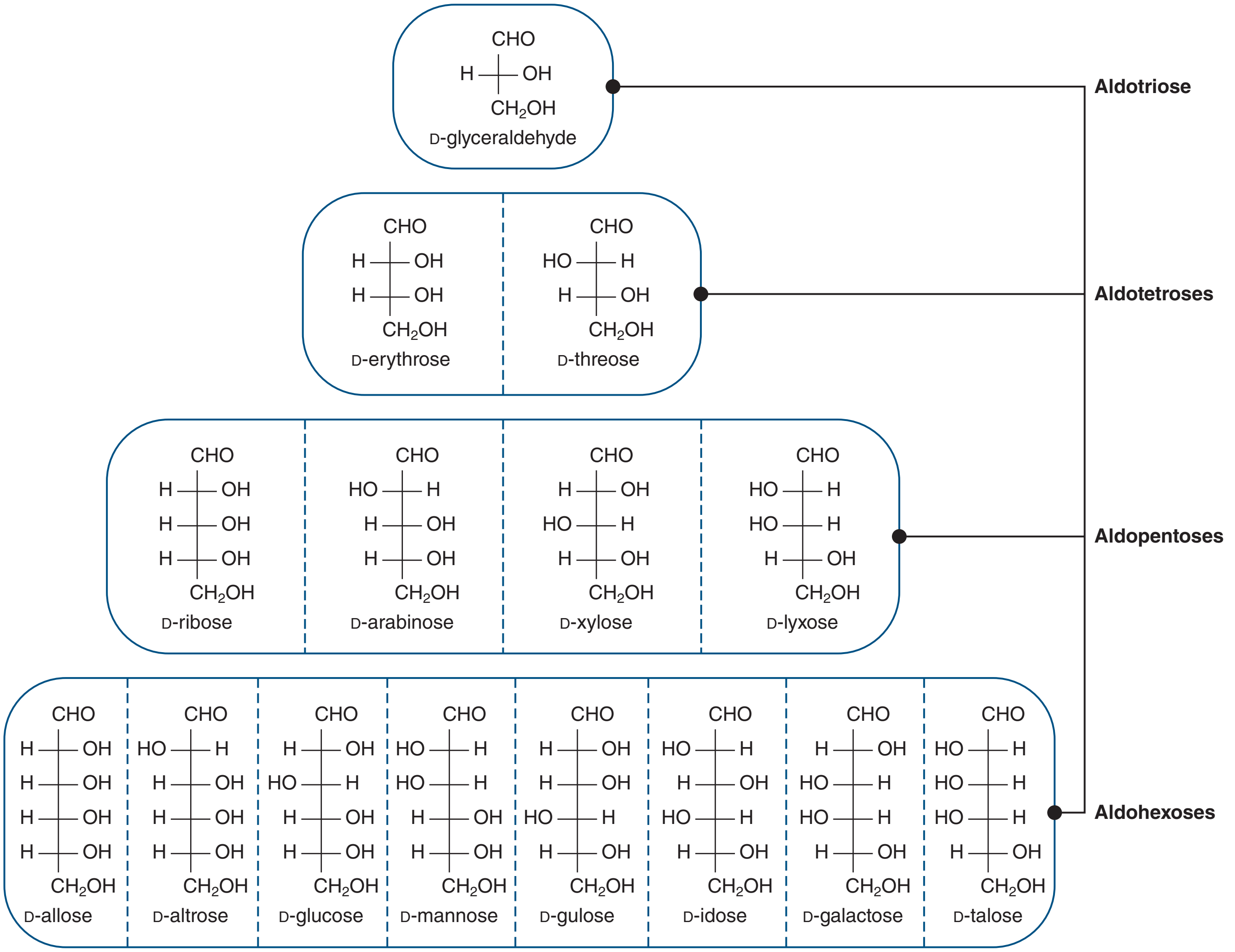
$$\begin{array}{rcl} & \text{CHO} & \\ & | & \\ \text{H}- & \text{C} & -\text{OH} \\ & | & \\ \text{HO}- & \text{C} & -\text{H} \\ & | & \\ \text{H}- & \text{C} & -\text{OH} \\ & | & \\ & \text{CH}_2\text{OH} & \end{array}$$

b.



$$\begin{array}{rcl} & \text{CHO} & \\ & | & \\ \text{HO}- & \text{C} & -\text{H} \\ & | & \\ \text{H}- & \text{C} & -\text{OH} \\ & | & \\ & \text{CH}_2\text{OH} & \end{array}$$

Most monosaccharides are aldoses, and almost all natural monosaccharides belong to the D series. The family of D-aldoses is shown in **Figure 17.10**. D-glyceraldehyde, the smallest monosaccharide with a chiral carbon, is the standard on which the whole series is based. Notice that



D-glyceraldehyde
Aldotriose
D-erythrose
D-threose
Aldotetroses
D-ribose
D-arabinose
D-xylose
D-lyxose
Aldopentoses
D-allose
D-altrose
D-glucose
D-mannose
D-gulose
D-idose
D-galactose
D-talose
Aldohexoses

FIGURE 17.10 The family of D-aldoses, shown in Fischer projections.

the bottom chiral carbon in each compound is directed to the right. The 2^n formula tells us there must be 2 trioses, 4 tetroses, 8 pentoses, and 16 hexoses. Half of those are the D compounds shown in **Figure 17.10**. The other half (not shown) are the enantiomers, or L compounds.

17.5 Properties of Monosaccharides

Learning Objective 6 Write reactions for monosaccharide oxidation and glycoside formation.

17.5A Physical Properties

Most monosaccharides (and disaccharides) are called sugars, because they taste sweet (see **Figure 17.11**). The degree of sweetness varies, as shown in **Table 17.2**. Fructose, the sweetest of the common sugars, is about 73% sweeter than sucrose, ordinary table sugar.

All carbohydrates are solids at room temperature, and because of the many —OH groups present, monosaccharide carbohydrates are extremely soluble in water. The —OH groups form numerous hydrogen bonds with the surrounding water molecules. In the body, this solubility allows carbohydrates to be transported rapidly in the circulatory system.

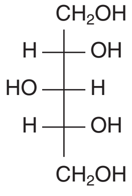
17.5B Chemical Properties, Cyclic Forms

So far we have represented the monosaccharides as open-chain polyhydroxy aldehydes and ketones. These representations are useful in discussing the structural features and stereochemistry of monosaccharides. However, we learned in **Section 14.3** that aldehydes

LOTTE
XYLITOL
SUGAR FREE GUM

Keith Homan/Shutterstock.com

FIGURE 17.11 Most chewing gums are sweetened with sugars that can increase the chance of cavities. Xylitol is the only sweetener that has been shown to reduce the potential for tooth decay.



xylitol

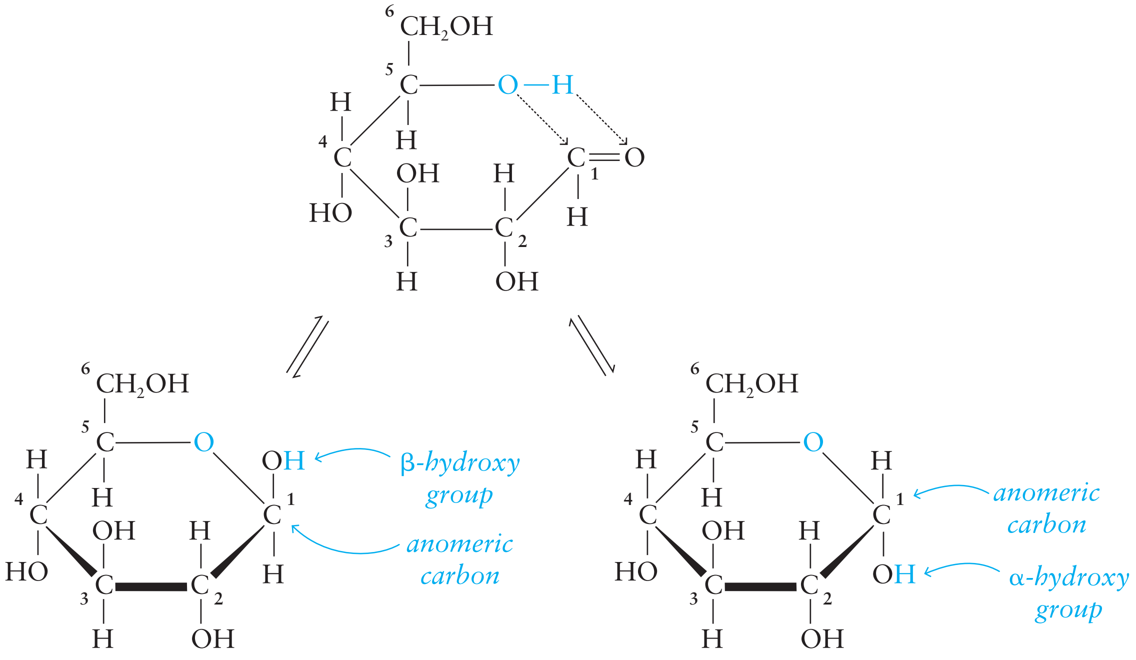
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

TABLE 17.2 The Relative Sweetness of Sugars (Sucrose = 1.00)

Sugar	Relative Sweetness	Type
Lactose	0.16	Disaccharide
Galactose	0.22	Monosaccharide
Maltose	0.32	Disaccharide
Xylose	0.40	Monosaccharide
Glucose	0.74	Monosaccharide
Sucrose	1.00	Disaccharide
Invert sugar	1.30	Mixture of glucose and fructose
Fructose	1.73	Monosaccharide

and ketones react with alcohols to form hemiacetals and hemiketals. When these functional groups are present in the same molecule, we noted that the result of their reaction is a stable cyclic structure. You should not be surprised then to find that all monosaccharides with at least five carbon atoms exist predominantly as cyclic hemiacetals and hemiketals.

To help depict the cyclization of glucose in Reaction 17.1, the open-chain structure has been bent around to position the functional groups in closer proximity. Notice the numbering of the carbon atoms that begins at the end of the chain, giving the lowest number to the carbonyl group carbon:



β-D-glucose α-D-glucose

(17.1)

pyranose ring A six-membered sugar ring system containing an oxygen atom.

Haworth structure A method of depicting three-dimensional carbohydrate structures.

anomeric carbon An acetal, ketal, hemiacetal, or hemiketal carbon atom giving rise to two stereoisomers.

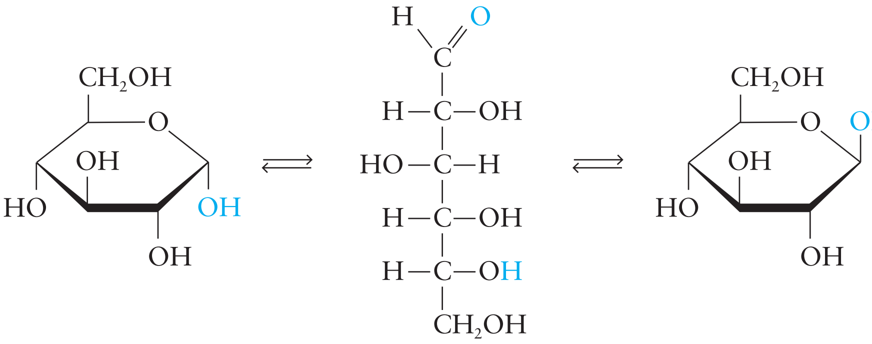
In the reaction, the alcohol group on carbon 5 adds to the aldehyde group on carbon 1. The result is a **pyranose ring**, a six-membered ring containing an oxygen atom. The attached groups have been drawn above or below the plane of the ring. This kind of drawing, called a **Haworth structure**, is used extensively in carbohydrate chemistry. Note that as the reaction occurs, a new chiral carbon is produced at position 1. Thus, two stereoisomers are possible: one with the —OH group pointing down (the α form), and the other with the —OH group pointing up (the β form). The C-1 carbon is called an **anomeric carbon**, and

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

the α and β forms are called **anomers**. Convenient condensed structures for the cyclic compounds omit the carbon atoms in the ring and the hydrogen atoms attached to the ring carbons, as shown in Reaction 17.2:

anomers Stereoisomers that differ in the three-dimensional arrangement of groups at the carbon of an acetal, ketal, hemiacetal, or hemiketal group.

(17.2)



α-D-glucose (36%)

D-glucose (0.02%)

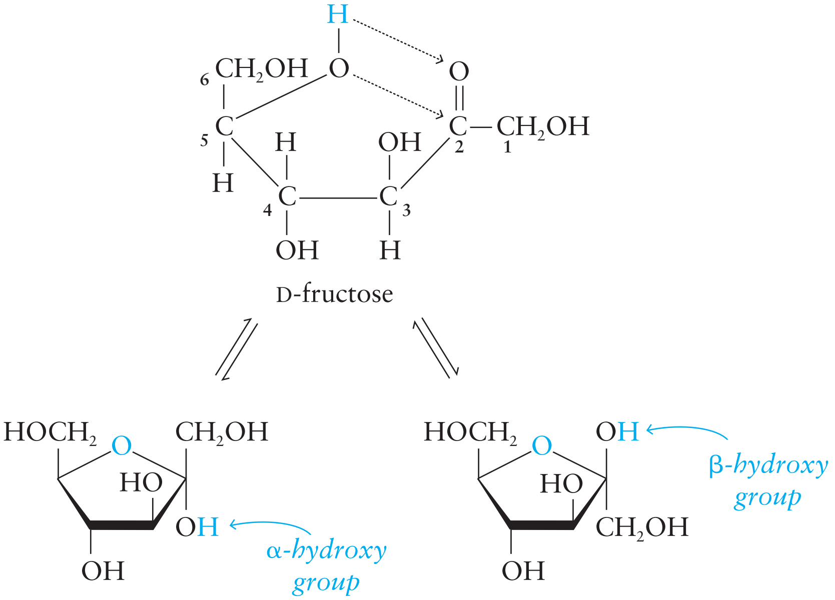
β-D-glucose (64%)

Thus, there are three forms of D-glucose: an open-chain structure and two ring forms. Because the reaction to form a cyclic hemiacetal is reversible, the three isomers of D-glucose are interconvertible. Studies indicate that the equilibrium distribution in water solutions is approximately 36% α-glucose, 0.02% open-chain form, and 64% β-glucose.

Other monosaccharides also form cyclic structures. However, some form five-membered rings, called **furanose rings**, rather than the six-membered kind. An example is D-fructose.

furanose ring A five-membered sugar ring system containing an oxygen atom.

The five-membered ring cyclization occurs like the ring formation in glucose. An alcohol adds across the carbonyl double bond (in this case, a ketone). The orientation of the —OH group at position 2 determines whether fructose is in the α or β form:



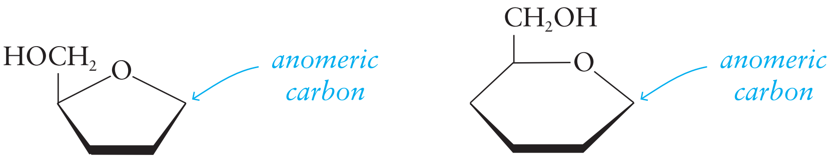
D-fructose

(17.3)

α-D-fructose

β-D-fructose

In drawing cyclic Haworth structures of monosaccharides, certain rules should be followed so that all our structures will be consistent. First we must draw the ring with its oxygen to the back:



furanose ring

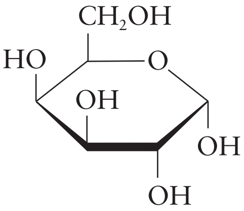
pyranose ring

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

We must also put the anomeric carbon on the right side of the ring. Then we envision the ring as planar with groups pointing up or down. The terminal —CH_2OH group (position 6) is always shown above the ring for D-monosaccharides.

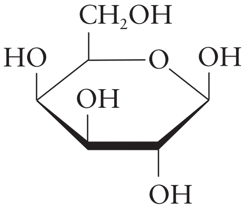
Example 17.7 Drawing Haworth Structures

The aldohexose D-galactose exists predominantly in cyclic forms. Given the structure below, draw the Haworth structure for the anomer. Label the new compound as α or β.



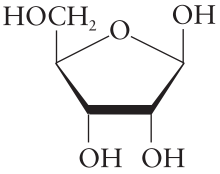
Solution

Draw the pyranose ring with the oxygen atom to the back. Number the ring starting at the right side. Position number 1 will be the anomeric carbon. Place the —OH group at position 1 in the up direction (β form) so that it is the anomer of the given compound. Place groups at the other positions exactly as they are in the given compound. Remember that anomers differ only in the position of the OH attached to the anomeric carbon.



β-D-galactose

✔ LEARNING CHECK 17.7 Draw the Haworth structure for the anomer of D-ribose. Label the new compound as α or β.



D-ribose

17.5C Oxidation

We learned in **Section 14.3** that aldehydes and those ketones that contain an adjacent —OH group are readily oxidized by an alkaline solution of Cu^{2+} (Benedict's reagent). Open-chain forms of monosaccharides exist as aldehydes or hydroxyketones and are readily oxidized. As the oxidation proceeds, the cyclic forms in equilibrium are converted to open-chain forms (see Le Châtelier's principle, **Section 8.8**) and also react.

reducing sugar A sugar that can be oxidized by Cu^{2+} solutions.

Sugars that can be oxidized by weak oxidizing agents are called **reducing sugars**. Thus, all monosaccharides are reducing sugars.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS 17.1

Sugar-Free Foods and Diabetes

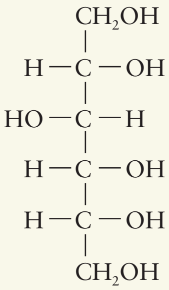
In the past, ice cream, cookies, and other sweets were considered to be off-limits to people with diabetes mellitus. However, advances in food science and a better understanding of the relationship between different foods and blood glucose levels have changed the rules, and sweet foods are now acceptable as part of the meal plan for people with diabetes. Diabetes is characterized by an impairment of the body's ability to utilize blood glucose.

Among the food science developments helpful to diabetics have been the discovery and commercial distribution of several synthetic noncarbohydrate sweetening agents. The U.S. Food and Drug Administration (FDA) has approved six products or recognized them as safe for the public, including people with diabetes: saccharin, neotame, acesulfame-K, aspartame, sucralose, and advantame.

Each of these sweeteners is noncaloric or provides very few calories when used in the quantities necessary to provide sweetness. Thus, these substances are useful dietary substitutes for sucrose or other calorie-laden sweeteners for people who wish to control calorie intake or for those who must avoid sugar, such as diabetics.

Other sweeteners that have expanded the food options for diabetics are known as sugar alcohols. These are carbohydrate derivatives, such as sorbitol, in which the carbon–oxygen double bond of the aldehyde or ketone has been converted to an alcohol:

New
mentos GUM
Trident
BreathSavers
© J. Schuyler

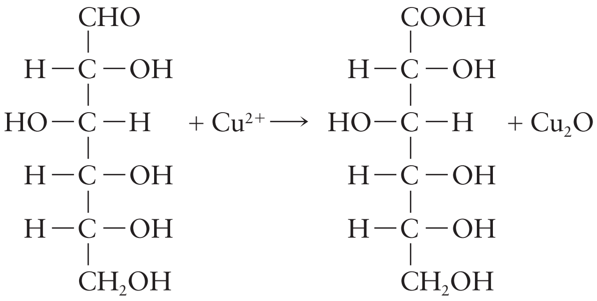

sorbitol

Sugar alcohols are incompletely absorbed during digestion and consequently contribute fewer calories than other carbohydrates. Sugar alcohols are found naturally in fruits. They are also produced commercially from carbohydrates for use in sugar-free candies, cookies, and chewing gum.

General reaction:

$$\text{Reducing sugar} + \underset{\text{deep blue solution}}{\underset{\text{(complex)}}{Cu^{2+}}} \rightarrow \text{oxidized compound} + \underset{\text{precipitate}}{\underset{\text{red-orange}}{Cu_2O}} \qquad (17.4)$$

Specific example:


D-glucose

D-gluconic acid

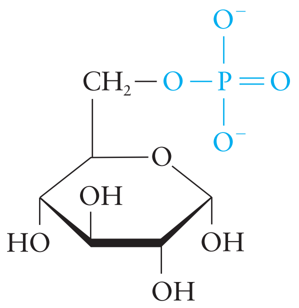
(17.5)

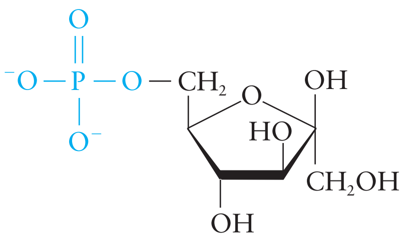
Benedict's reagent is deep blue in color. As the open-chain form of a monosaccharide is oxidized, Cu^{2+} is reduced and precipitated as Cu_2O, a red-orange solid.

When we study energy transformations in cells (see **Chapters 22 and 23**), we will encounter many reactions that involve the stepwise oxidation of carbohydrates to CO_2 and H_2O. The controlled oxidation of carbohydrates in the body serves as an important source of heat and other forms of energy.

17.5D Phosphate Esters

The hydroxy groups of monosaccharides can behave as alcohols and react with acids to form esters. Esters formed from phosphoric acid and various monosaccharides are found in all cells, and some serve as important intermediates in carbohydrate metabolism. The structures of two representative phosphate esters are shown below:

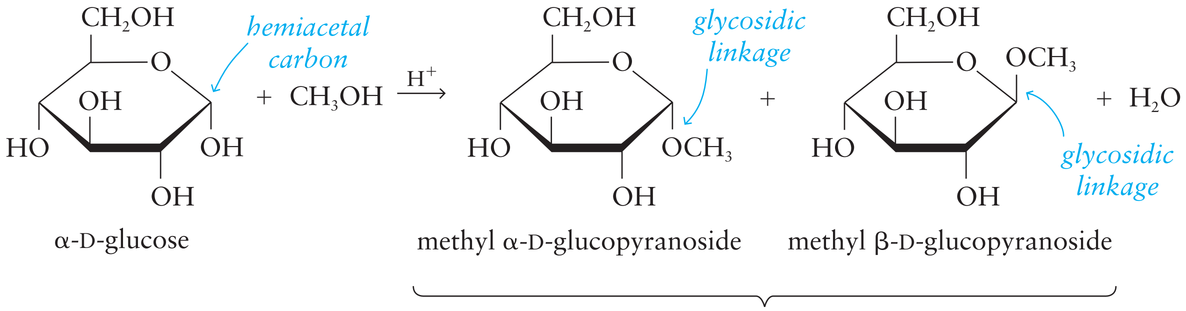

glucose 6-phosphate


fructose 6-phosphate

17.5E Glycoside Formation

glycoside Another name for a carbohydrate containing an acetal or ketal group.

In **Section 14.3**, we learned that hemiacetals and hemiketals can react with alcohols in acid solutions to yield acetals and ketals, respectively. Thus, cyclic monosaccharides (hemiacetals and hemiketals) readily react with alcohols in the presence of acid to form acetals and ketals. The general name for these carbohydrate products is **glycosides**. The reaction of α-D-glucose with methanol is shown in Reaction 17.6.



α-D-glucose

methyl α-D-glucopyranoside

methyl β-D-glucopyranoside

glycosides

(17.6)

glycosidic linkage The carbon–oxygen–carbon linkage that joins the components of a glycoside to the ring.

The hemiacetal in glucose is located at position 1, and the acetal thus forms at that same position. All the other —OH groups in glucose are ordinary alcohol groups and do not react under these conditions. As the glycoside reaction takes place, a new bond is established between the pyranose ring and the —OCH_3 groups. The new group may point up or down from the ring. Thus, a mixture of α- and β-glycosides is formed. The new carbon–oxygen–carbon linkage that joins the components of the glycoside is called a **glycosidic linkage**.

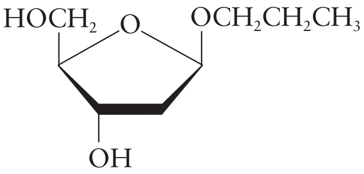
Although carbohydrate cyclic hemiacetals and hemiketals are in equilibrium with open-chain forms of the monosaccharides, the glycosides (acetals and ketals) are much more stable and do not exhibit open-chain forms. Therefore, glycosides of monosaccharides are not reducing sugars.

As we'll see later in this chapter, both disaccharides and polysaccharides are examples of glycosides in which monosaccharide units are joined together by acetal (glycosidic) linkages.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

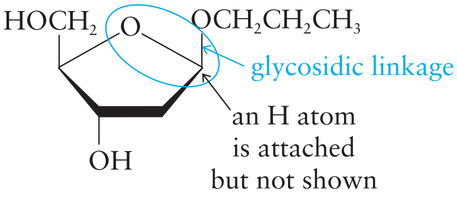
Example 17.8 Identifying Glycosidic Linkages

Deoxyribose is a component of deoxyribonucleic acid (DNA). A modification of deoxyribose is shown below. Circle any acetal or ketal group and use an arrow to identify the glycosidic linkage.


HOCH$_2$
O
OCH$_2$CH$_2$CH$_3$
OH

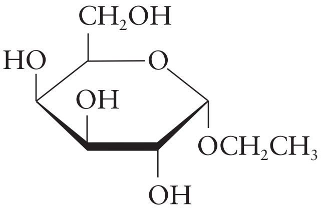
Solution

Look for the presence of a carbon atom with two oxygens attached. That carbon also has an attached hydrogen atom, which makes the group an acetal.

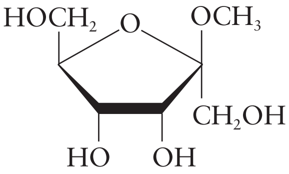

HOCH$_2$
O
OCH$_2$CH$_2$CH$_3$
glycosidic linkage
an H atom
is attached
but not shown
OH

✔ **LEARNING CHECK 17.8** Two glycosides are shown below. Circle any acetal or ketal groups and use an arrow to identify the glycosidic linkages.

a.


CH$_2$OH
HO
O
OH
OCH$_2$CH$_3$
OH

b.

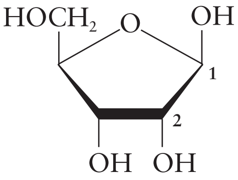

HOCH$_2$
O
OCH$_3$
CH$_2$OH
HO
OH

17.6 Important Monosaccharides

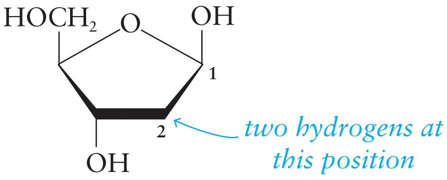
Learning Objective 7 Describe uses for important monosaccharides.

17.6A Ribose and Deoxyribose

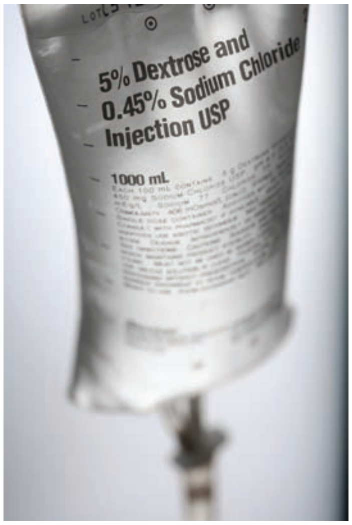
Two pentoses, ribose and deoxyribose, are extremely important because they are used in the synthesis of nucleic acids (DNA and RNA), substances essential in protein synthesis and the transfer of genetic material (see **Chapter 21**). Ribose (along with phosphate groups) forms the long chains that make up ribonucleic acid (RNA). Deoxyribose (along with phosphate groups) forms the long chains of deoxyribonucleic acid (DNA). Deoxyribose differs from ribose in that the OH group on carbon 2 has been replaced by a hydrogen atom (deoxy form).


HOCH$_2$
O
OH
1
2
OH
OH

β-D-ribose


HOCH$_2$
O
OH
1
2
OH
two hydrogens at
this position

β-D-deoxyribose

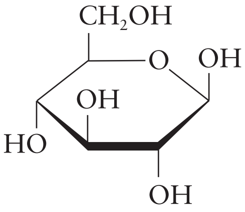


Thammasak Lek/Shutterstock.com

FIGURE 17.12 A dextrose (glucose) solution prepared for intravenous use.

17.6B Glucose

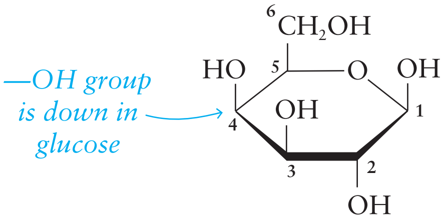
Of the monosaccharides, the hexose glucose is the most important nutritionally and the most abundant in nature. Glucose is present in honey and fruits such as grapes, figs, and dates. Ripe grapes, for example, contain 20–30% glucose. Glucose is sometimes called dextrose. Glucose is also known as blood sugar, because it is the sugar transported by the blood to body tissues to satisfy energy requirements (see **Figure 17.12**). Other sugars absorbed into the body must be converted to glucose by the liver. Glucose is commonly used as a sweetener in confections and other foods, including some baby foods.



β-D-glucose

17.6C Galactose

Galactose is a hexose with a structure very similar to that of glucose. The only difference between the two is the orientation of the hydroxy group attached to carbon 4. Like glucose, galactose can exist in α, β, or open-chain forms; the β form is shown below:



β-D-galactose

Galactose is synthesized in the mammary glands, where it is incorporated into lactose, the sugar found in milk. It is also a component of substances present in nerve tissue.

17.6D Fructose

Fructose (**Section 17.5**) is the most important ketohexose. It is also known as levulose and, because of its presence in many fruits, fruit sugar. It is present in honey in a 1:1 ratio with glucose and is abundant in corn syrup. This sweetest of the common sugars is important as a food sweetener because less fructose is needed than other sugars to achieve the same degree of sweetness.

17.7 Disaccharides

Learning Objective 8 Draw the structures and list sources and uses for important disaccharides.

Learning Objective 9 Write reactions for the hydrolysis of disaccharides.

Disaccharides are sugars composed of two monosaccharide units linked together by the acetal or ketal linkages described earlier. They can be hydrolyzed to yield their monosaccharide building blocks by boiling with dilute acid or reacting them with appropriate enzymes. Nutritionally, the most important members of this group are maltose, lactose, and sucrose.

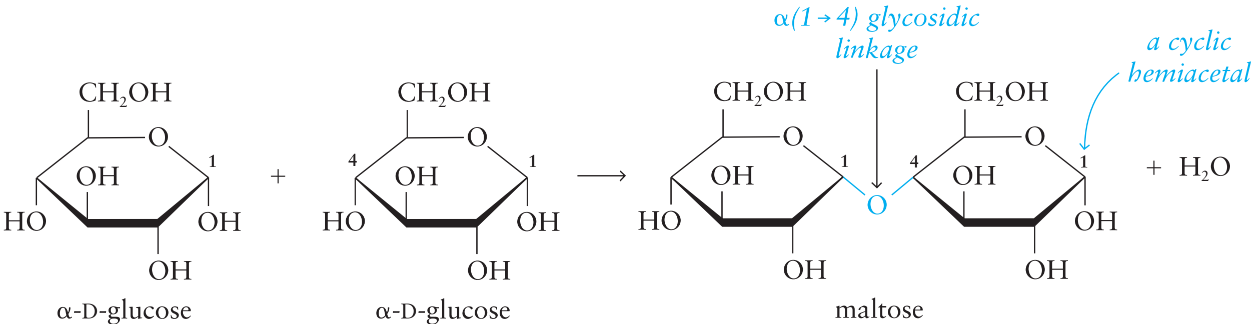
17.7A Maltose

Maltose, also called malt sugar, contains two glucose units joined by a glycosidic linkage between carbon 1 of the first glucose unit and carbon 4 of the second unit (Reaction 17.7). The configuration of the linkage on carbon 1 in the glycosidic linkage between glucose units is α, and the linkage is symbolized α(1 → 4) to indicate this fact.

STUDY TOOLS 17.1

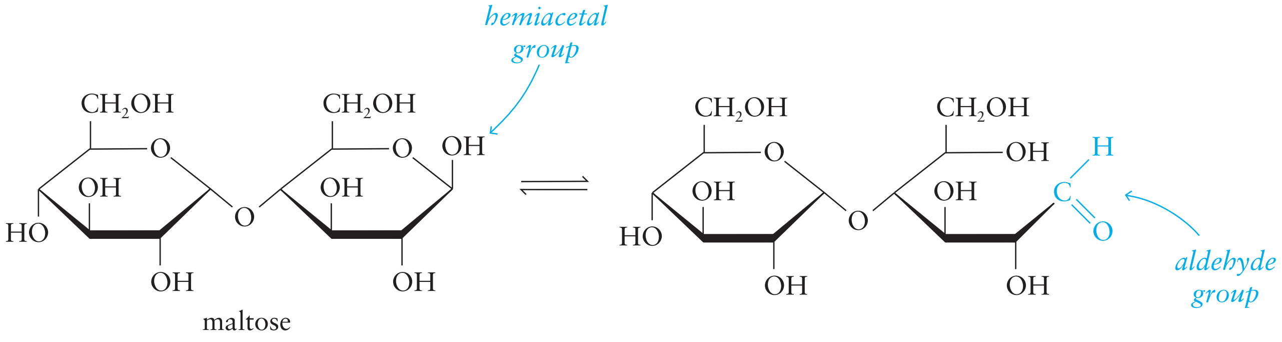
Biomolecules: A New Focus

The chapters on organic chemistry (see **Chapters 11–16**) were organized around the functional group concept. Each chapter dealt with a particular functional group or related groups. The nomenclature, properties, and uses of the compounds were discussed. The focus is different in this and the next four chapters (lipids, proteins, enzymes, and nucleic acids). Each of these chapters is devoted to a particular class of biomolecules—substances closely associated with life. Reactions and nomenclature receive much less emphasis; more time is spent describing structures and how they contribute to the processes of living organisms. Another key difference between these and earlier chapters is the reduced emphasis on mastering specific skills, such as solving numerical problems, balancing equations, and naming compounds. More attention should now be given to recognizing structures and understanding key terms and processes. It is a good time to increase your efforts to highlight important concepts in both the text and your lecture notes.



(17.7)

Notice that maltose contains both an acetal carbon (left glucose unit, position 1) and a hemiacetal carbon (right glucose unit, position 1). The —OH group at the hemiacetal position can point either up or down (the β is shown). The presence of a hemiacetal group also means that the right glucose ring can open up to expose an aldehyde group. Thus, maltose is a reducing sugar (Reaction 17.8).



(17.8)

Maltose, which is found in germinating grain, is formed during the digestion (hydrolysis) of starch to glucose. Its name is derived from the fact that during the germination (or malting) of barley, starch is hydrolyzed, and the disaccharide is formed. On hydrolysis, maltose forms two molecules of D-glucose:

$$\text{maltose} + H_2O \xrightarrow{H^+} \text{D-glucose} + \text{D-glucose} \qquad (17.9)$$

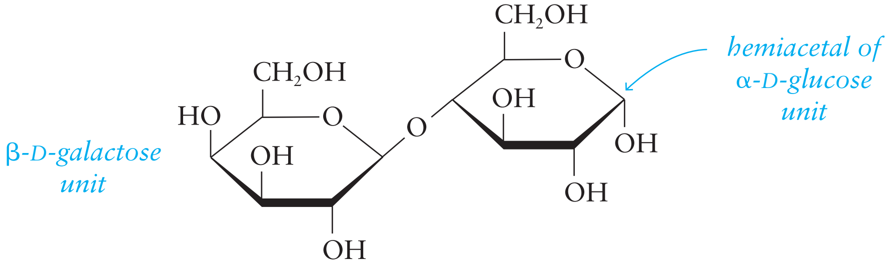
17.7B Lactose

Lactose, or milk sugar, constitutes 5% of cow's milk and 7% of human milk by weight (see **Figure 17.13**). Pure lactose is obtained from whey, the watery by-product of cheese production. Lactose is composed of one molecule of D-galactose and one of D-glucose. The linkage between the two sugar units is β(1 → 4):

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

© Michael C. Slabaugh

FIGURE 17.13 Cow's milk is about 5% lactose. What two products form when the lactose is hydrolyzed in the child's digestive system?


CH₂OH
O
OH
OH
OH
CH₂OH
HO
O
OH
O
OH
β-D-galactose unit

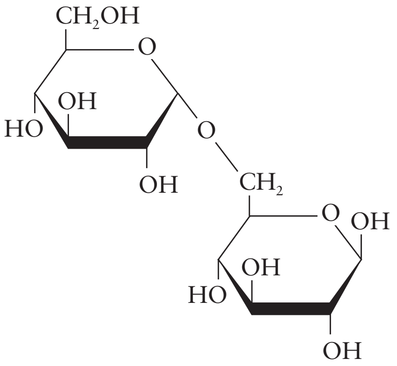
hemiacetal of α-D-glucose unit

lactose

The presence of a hemiacetal group in the glucose unit makes lactose a reducing sugar.

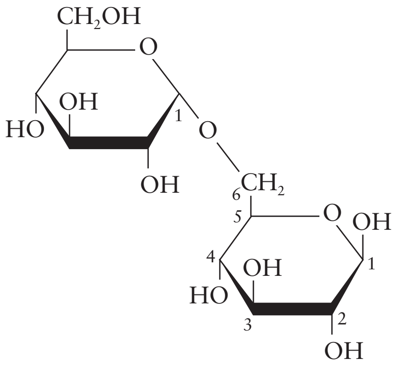
Example 17.9 Identifying Disaccharide Linkages

Gentiobiose is a disaccharide formed when glucose is caramelized by heating. Describe the linkage between the two components.

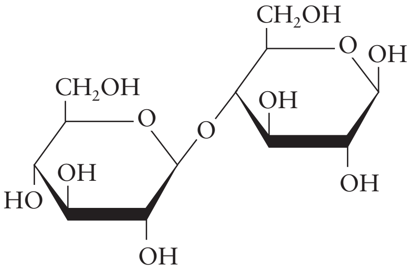

CH₂OH
O
OH
HO
O
OH
CH₂
O
OH
OH
HO
OH

Solution

At position 1 in the glucose unit on the left, the oxygen is directed up ward, so it is (β). The glucose unit on the right is connected through position 6, so the linkage is β(1→6).


CH₂OH
O
OH
HO
1
O
OH
6
CH₂
5
O
OH
4
OH
1
HO
3
2
OH

✔ LEARNING CHECK 17.9 The disaccharide cellobiose is formed upon the hydrolysis of cellulose. Describe the linkage between the two units.


CH₂OH
O
OH
CH₂OH
O
O
OH
OH
HO
OH
OH

17.7C Sucrose

The disaccharide sucrose, common household sugar, is extremely abundant in the plant world. It occurs in many fruits, in the nectar of flowers (see **Figure 17.14**), and in the juices of many plants, especially sugar cane and sugar beets, the commercial sources. Sucrose contains two monosaccharides, glucose and fructose, joined together by a linkage that is α from carbon 1 of glucose and β from carbon 2 of fructose:

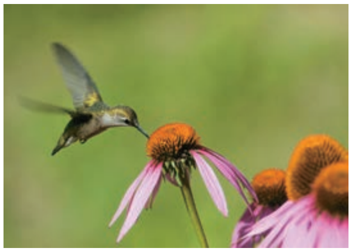
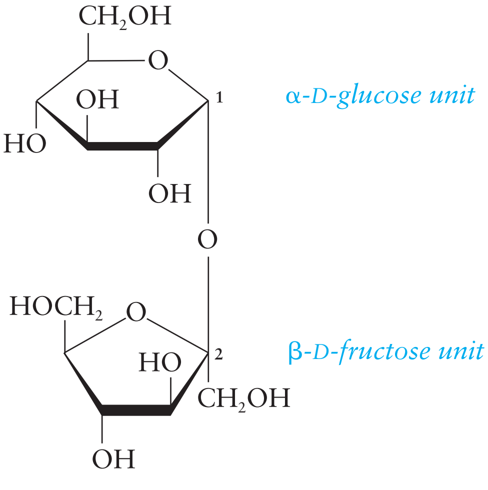
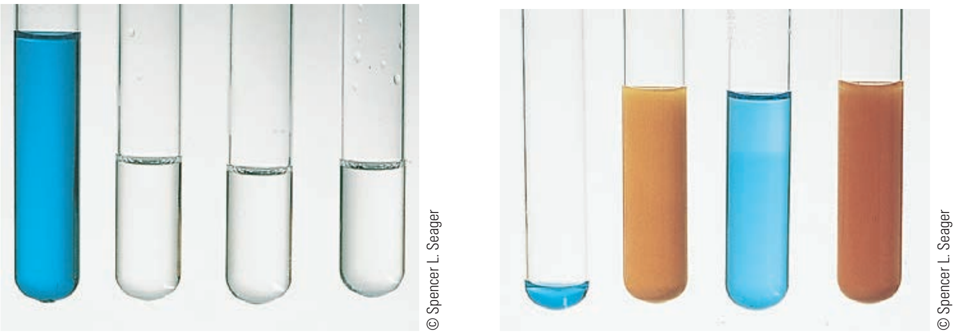

iStock.com/YanC

FIGURE 17.14 Hummingbirds depend on the sucrose and other carbohydrates of nectar for their energy.



sucrose

Neither ring in the sucrose molecule contains a hemiacetal or hemiketal group that is necessary for ring opening. This is true because the anomeric positions in both glucose and fructose are part of the glycosidic linkage that connects the rings to each other. Thus, in contrast to maltose and lactose, both rings of sucrose are locked in the cyclic form, and sucrose is therefore not a reducing sugar (see **Figure 17.15**).


© Spencer L. Seager

© Spencer L. Seager

1 From left to right, four test tubes containing Benedict's reagent, 2% maltose solution, 2% sucrose solution, and 2% lactose solution.

2 Both maltose and lactose are reducing sugars. The sucrose has remained unreacted.

FIGURE 17.15 Benedict's test on disaccharides.

The hydrolysis of sucrose (see **Figure 17.16**) produces a 1:1 mixture of D-glucose and D-fructose called **invert sugar** (Reaction 17.10):

$$\text{sucrose} + H_2O \xrightarrow{H^+} \text{D-glucose} + \text{D-fructose} \qquad (17.10)$$

invert sugar A mixture of equal amounts of glucose and fructose.

This mixture is sweeter than the original sucrose (see **Table 17.2**).

When sucrose is cooked with acid-containing fruits or berries, partial hydrolysis takes place, and some invert sugar is formed. The jams and jellies prepared in this manner are actually sweeter than the pure sugar originally put in them. **Table 17.3** summarizes some features of the three disaccharides we have discussed.

Antonio Gravante/Shutterstock.com

FIGURE 17.16 Sucrose is hydrolyzed by bees in making honey. Why is honey sweeter than the starting sucrose?

TABLE 17.3 Some Important Disaccharides

Name	Monosaccharide Constituents	Glycoside Linkage	Source
Maltose	Two glucose units	$\alpha(1 \rightarrow 4)$	Hydrolysis of starch
Lactose	Galactose and glucose	$\beta(1 \rightarrow 4)$	Mammalian milk
Sucrose	Glucose and fructose	$\alpha\text{-}1 \rightarrow \beta\text{-}2$	Sugar cane and sugar beet juices

17.8 Polysaccharides

Learning Objective 10 Describe the structures and list sources and uses for important polysaccharides.

Just as two sugar units are linked together to form a dissacharide, additional units can be added to form higher saccharides. Nature does just this in forming polysaccharides, which are condensation polymers containing thousands of units. Because of their size, polysaccharides are not water soluble, but their many hydroxy groups become hydrated individually when exposed to water, and some polysaccharides form thick colloidal dispersions when heated in water. Thus, the polysaccharide known as starch can be used as a thickener in sauces, gravies, pie fillings, and other food preparations. As shown in **Table 17.4**, the properties of polysaccharides differ markedly from those of monosaccharides and disaccharides.

TABLE 17.4 Properties of Polysaccharides Compared with Those of Monosaccharides and Disaccharides

Property	Monosaccharides and Disaccharides	Polysaccharides
Molecular weight	Low	Very high
Taste	Sweet	Tasteless
Solubility in water	Soluble	Insoluble or form colloidal dispersions
Size of particles	Pass through a membrane	Do not pass through a membrane
Test with Cu^{2+} for reducing sugars	Positive (except for sucrose)	Negative

17.8A Starch

Starch is a polymer consisting entirely of D-glucose units. It is the major storage form of D-glucose in plants. Two starch fractions, amylose (10–20%) and amylopectin (80–90%), can usually be isolated from plants. Amylose is made up of long unbranched chains of glucose units connected by $\alpha(1 \rightarrow 4)$ linkages (see **Figure 17.17**). This is the same type of linkage found in maltose. The long chain, often containing between 1000 and 2000 glucose units, is flexible enough to allow the molecules to twist into the shape of a helix (see **Figure 17.18a**).

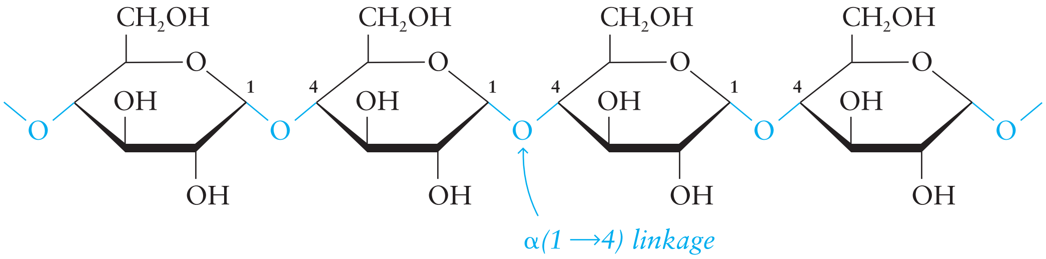
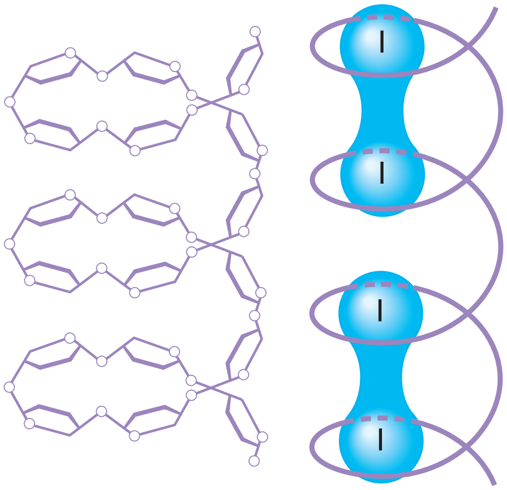


FIGURE 17.17 The structure of amylose.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

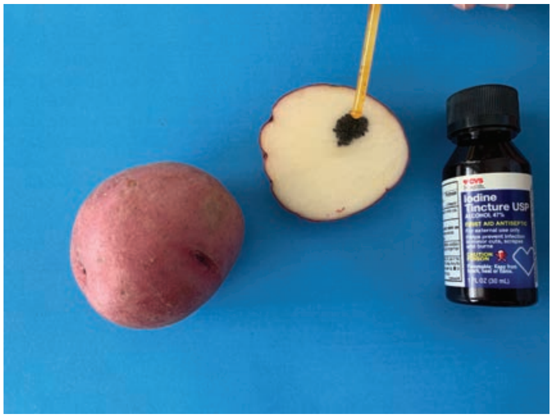
An important test for the presence of starch is the reaction that occurs between iodine, I_2, and the coiled form of amylose. The product of the reaction is deep blue in color (see **Figure 17.19**) and is thought to consist of the amylose helix filled with iodine molecules. This same iodine reaction is also widely used to monitor the hydrolysis of starch. The color gradually fades and finally disappears, as starch is hydrolyzed by either acid or enzymes to form dextrins (smaller polysaccharides), then maltose, and finally glucose. The disappearance of the blue iodine color is thought to be the result of the breakdown of the starch helix.



a The helical conformation of the amylose chain

b The starch–iodine complex

FIGURE 17.18 The molecular conformation of starch and the starch–iodine complex.



Michael Slabaugh

FIGURE 17.19 A dark bluish-black color is the characteristic result when a solution of iodine encounters the starch in potatoes. What other foods would you expect to give a positive starch test?

Amylopectin, the second component of starch, is not a straight-chain molecule like amylose but contains random branches. The branching point is the α(1 → 6) glycosidic linkage (see **Figure 17.20**). There are usually 24 to 30 D-glucose units, all connected by α(1 → 4) linkages, between each branch point of amylopectin. These branch points give amylopectin the appearance of a bushy molecule. Amylopectin contains as many as 10^5 glucose units in one gigantic molecule.

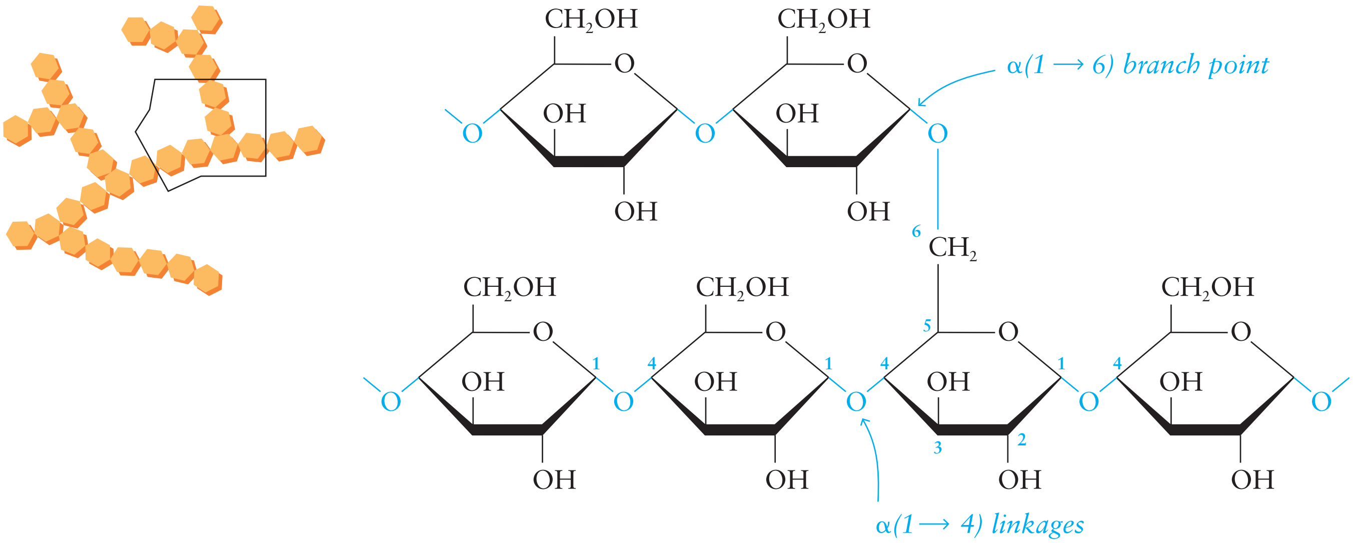


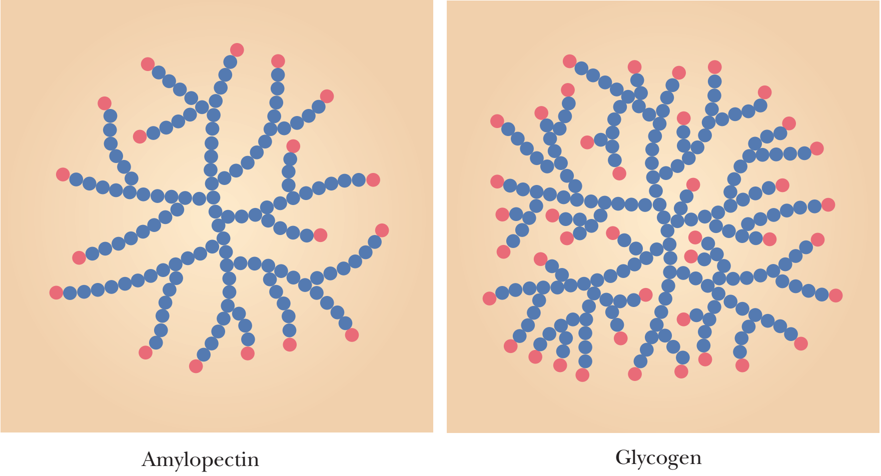
FIGURE 17.20 The partial structure of an amylopectin molecule. Glycogen has a similar structure.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

17.8B Glycogen

The polysaccharide glycogen is sometimes called animal starch because it is a storage carbohydrate for animals that is analogous to the starch of plants. It is especially abundant in the liver and muscles, where excess glucose taken in by an animal is stored for future use. On hydrolysis, glycogen forms D-glucose, which helps maintain the normal blood sugar level and provide the muscles with energy. Structurally, glycogen is very similar to amylopectin, containing both α(1 → 4) and α(1 → 6) linkages between glucose units (see **Figure 17.21**). The main difference between amylopectin and glycogen is that glycogen is even more highly branched as there are only 8 to 12 D-glucose units between branch points.

FIGURE 17.21 A simplified representation of the branched polysaccharide glycogen (branches every 8–12 glucose units). Amylopectin is much less densely branched (branches every 24–30 glucose units). Each small circle represents a single glucose unit.



17.8C Cellulose

Cellulose is the most important structural polysaccharide and is the single most abundant organic compound on Earth (see **Figure 17.22**). It is the material in plant cell walls that provides strength and rigidity. Wood is about 50% cellulose. Like amylose, cellulose is a linear polymer consisting of D-glucose units joined by the 1 → 4 linkage. It may contain 300 to 3000 glucose units in one molecule. The main structural difference between amylose and cellulose is that all the 1 → 4 glycosidic linkages in cellulose are

FIGURE 17.22 Cellulose and the plant kingdom are responsible for much of the world's natural beauty.

© Michael C. Slabaugh

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS 17.2

Put Fiber into Snacks and Meals

Fiber is a type of carbohydrate found only in food derived from plants. It is not found in any meat or dairy products. While not considered to be a "nutrient," fiber still plays a vital role in maintaining good digestive and cardiovascular health, as well as weight loss and weight maintenance. Research indicates that eating a diet high in fiber also reduces the risk of developing cancer. Fiber, along with adequate fluid intake, plays a cleansing role in the body. The recommended daily fiber intake is 21–25 grams for women and 30–38 grams for men. Nutrition labels on foods list fiber content. This is usually given in grams per serving, or in percentage of daily recommended amounts per serving. Most foods that contain fiber offer small amounts (2–5 grams) per serving, so including fiber throughout the day in snacks as well as meals is important in order to reach a goal of 25–30 grams per day.

Knowing which foods contain fiber assists in making healthy choices and reaching daily fiber intake goals. Since many people eat fruits as a snack, fruits are a good place to start when counting daily fiber intake. Fresh raspberries contain 8 grams of fiber per cup, which is more than 30% of the daily fiber intake recommendation. Apples, oranges, and bananas each contain 3 to 5 grams per serving. Vegetable snacks that contribute fiber, such as raw broccoli and carrots, offer convenience and portability. Other vegetables might not make suitable raw snacks, but can add significant fiber to the diet when added to daily meals. Good vegetable choices are cooked peas, beans, corn, and artichokes. Grains and grain products are significant sources of fiber.

A great way to boost fiber intake is to sprinkle high-fiber foods on normally eaten food. Oat bran, wheat bran, ground flax seeds, or berries can easily be added to sweet or savory foods such as oatmeal, pancakes, soups, baked potatoes, casseroles, or salads. Any meal can become a high-fiber meal with a sprinkling of bran.

Nitr/Shutterstock.com

Fruits are a good source of fiber.

β instead of α (see **Figure 17.23**). This seemingly small difference causes tremendous differences between amylose and cellulose. The shapes of the molecules are quite different. The α(1 → 4)-linked amylose tends to form loose spiral structures (see **Figure 17.18**), whereas β(1 → 4)-linked cellulose tends to form extended straight chains. These chains become aligned side by side to form well-organized, water-insoluble fibers in which the hydroxy groups form numerous hydrogen bonds with the neighboring chains. These parallel chains of cellulose confer rigidity and strength to the molecules.

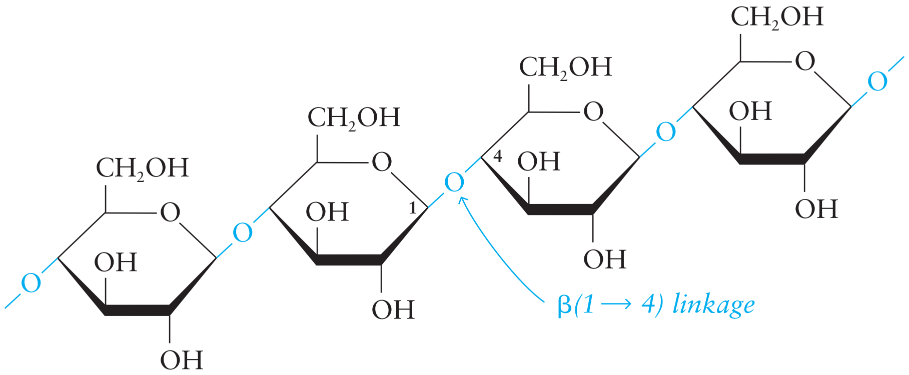


FIGURE 17.23 The structure of cellulose.

Second, although starch with its α linkages is readily digestible, humans and other animals lack the necessary enzymes to hydrolyze the β linkages of cellulose. Thus, cellulose passes unchanged through the digestive tract and does not contribute to the caloric value of food. However, it still serves a useful purpose in digestion. Cellulose, a common constituent of dietary fiber, is the roughage that provides bulk, stimulates contraction of the intestines, and aids the passage of food through the digestive system.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Animals that use cellulose as a food do so only with the help of bacteria that possess the necessary enzymes for breakdown. Herbivores such as cows, sheep, and horses are animals in this category. Each has a colony of such bacteria somewhere in the digestive system and uses the simple carbohydrates resulting from the bacterial hydrolysis of cellulose. Fortunately, the soil also contains organisms with appropriate enzymes. Otherwise, debris from dead plants would accumulate rather than disappear through biodegradation.

Health Career Description

DENTAL ASSISTANT

A wide range of duties exists within the dental assisting field. Some assistants perform mostly office support and help with making the clients comfortable, as well as collecting insurance information and payments; whereas, some assistants perform treatments such as applying topical anesthetics, performing coronal polishing, or applying sealants or fluoride treatments.

Assistants that provide only office assistance and help with patients are not required to have any certification, but those who practice dental treatments typically require certification or licensure. Some programs are 1 year long and end in certification; others span 2 years and culminate in an associate's degree.

The American Dental Association lists the duties of a dental assistant as:

- assisting the dentist during a variety of treatment procedures.
- taking and developing dental radiographs (x-rays).
- asking about the patient's medical history and taking blood pressure and pulse.
- serving as an infection control officer, developing infection control protocol and preparing and sterilizing instruments and equipment.
- helping patients feel comfortable before, during, and after dental treatment.
- providing patients with instructions for oral care following surgery or other dental treatment procedures, such as the placement of a restoration (filling).
- teaching patients appropriate oral hygiene strategies to maintain oral health (e.g., tooth brushing, flossing, and nutritional counseling).
- taking impressions of patients' teeth for study casts (models of teeth).
- performing office management tasks that often require the use of a personal computer.
- communicating with patients and suppliers (e.g., scheduling appointments, answering the telephone, billing, and ordering supplies).
- helping to provide direct patient care in all dental specialties, including orthodontics, pediatric dentistry, periodontics and oral surgery.

A dental assistant is not a dental hygienist. Hygienists' work focuses on cleaning the teeth. Dental hygienists typically hold at least an associate's degree and often a bachelor's degree. According to the Bureau of Labor Statistics, the average salary for a dental assistant is $38,000 annually and is "growing at 11% (much faster than average)." Demand for dental assistant jobs is expected to continue to grow and is a secure bet for a career in demand for the foreseeable future.

Sources: American Dental Association. Dental Assistants. Retrieved Apr. 21, 2020 from: https://www.ada.org/en/education-careers/careers-in-dentistry/dental-team-careers/dental-assistant; Bureau of Labor Statistics. Dental Assistants. Retrieved April 21, 2020 from: https://www.bls.gov/ooh/healthcare/dental-assistants.htm

Concept Summary

17.1 Classes of Carbohydrates

Learning Objective: Can you describe the four major functions of carbohydrates in living organisms? Can you classify carbohydrates as monosaccharides, disaccharides, or polysaccharides?

- Carbohydrates are polyhydroxy aldehydes or ketones, or substances that yield such compounds on hydrolysis.
- Carbohydrates are used as energy sources, biosynthetic intermediates, energy storage, and structural elements in organisms.
- Carbohydrates can exist either as single units (monosaccharides) or joined together in molecules ranging from two units (disaccharides) to hundreds of units (polysaccharides).

17.2 The Stereochemistry of Carbohydrates

Learning Objective: Can you identify molecules possessing chiral carbon atoms?

- Carbohydrates, along with many other natural substances, exhibit a type of isomerism in which two isomers are mirror images of each other.

- The two isomers are called enantiomers and contain a chiral carbon atom.
- When a molecule has more than one chiral carbon, the maximum number of stereoisomers possible is 2^n, where n is the number of chiral carbons.

17.3 Fischer Projections

Learning Objective: Can you use Fischer projections to represent D and L compounds?

- A useful way of depicting the structure of chiral molecules employs crossed lines (Fischer projections) to represent chiral carbon atoms.
- The prefixes D- and L- are used to distinguish between enantiomers.
- Signs indicating the rotation of plane-polarized light to the right (+) or to the left (–) may also be used to designate enantiomers.

17.4 Monosaccharides

Learning Objective: Can you classify monosaccharides as aldoses or ketoses, and classify them according to the number of carbon atoms they contain?

- Monosaccharides that contain an aldehyde group are called aldoses.
- Those containing a ketone group are ketoses.
- Monosaccharides are also classified by the number of carbon atoms as trioses, tetroses, etc.
- Most natural monosaccharides belong to the D family.

17.5 Properties of Monosaccharides

Learning Objective: Can you write reactions of monosaccharide oxidation and glycoside formation?

- Monosaccharides are sweet-tasting solids that are very soluble in water.
- Noncarboydrate low-calorie sweeteners such as aspartame have been developed as sugar substitutes.
- Pentoses and hexoses form cyclic hemiacetals or hemiketals whose structures can be represented by Haworth structures.
- Two isomers referred to as anomers (the α and β forms) are produced in the cyclization reaction.
- All monosaccharides are oxidized by Benedict's reagent and are called reducing sugars.
- Monosaccharides can react with alcohols to produce acetals or ketals that are called glycosides.

17.6 Important Monosaccharides

Learning Objective: Can you describe uses for important monosaccharides?

- Ribose and deoxyribose are important as components of nucleic acids.
- The hexoses glucose, galactose, and fructose are the most important nutritionally and the most abundant in nature.
- Glucose, also known as blood sugar, is transported within the bloodstream to body tissues, where it supplies energy.

17.7 Disaccharides

Learning Objective: Can you draw the structures and list sources and uses for important disaccharides? Can you write reactions for the hydrolysis of disaccharides?

- Glycosidic linkages join monosaccharide units together to form disaccharides.
- Three important disaccharides are maltose (two glucose units $\alpha(1 \rightarrow 4)$-linked), lactose (a galactose linked to glucose by a $\beta(1 \rightarrow 4)$ glycosidic linkage), and sucrose (α-glucose joined to β-fructose).

17.8 Polysaccharides

Learning Objective: Can you describe the structures and list sources and uses for important polysaccharides?

- Cellulose, starch, and glycogen are three important polysaccharides.
- Starch is the major storage form of glucose in plants.
- Glycogen is the storage form of glucose in animals.
- Cellulose is the structural material of plants.

Key Terms and Concepts

Anomeric carbon (17.5)
Anomers (17.5)
Biochemistry (Introduction)
Biomolecule (Introduction)
Carbohydrate (17.1)
Chiral (17.2)
Chiral carbon (17.2)
Dextrorotatory (17.3)
Disaccharide (17.1)
Enantiomers (17.2)
Fischer projection (17.3)
Furanose ring (17.5)
Glycoside (17.5)
Glycosidic linkage (17.5)
Haworth structure (17.5)
Invert sugar (17.7)
Levorotatory (17.3)
Monosaccharide (17.1)
Optically active molecule (17.3)
Polysaccharide (17.1)
Pyranose ring (17.5)
Reducing sugar (17.5)

Key Equations

1. Oxidation of a sugar (**Section 17.5**):	reducing sugar + $Cu^{2+} \rightarrow$ oxidized compound + Cu_2O	Reaction 17.4
2. Glycoside formation (**Section 17.5**):	monosaccharide + alcohol $\xrightarrow{H^+}$ acetals or ketals	
3. Hydrolysis of disaccharides (**Section 17.7**):	disaccharide + $H_2O \xrightarrow[\text{enzymes}]{H^+ \text{ or}}$ two monosaccharides	

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Classes of Carbohydrates (Section 17.1)

17.1 What are the four important roles of carbohydrates in living organisms?

17.2 Describe whether each of the following substances serves primarily as an energy source, a form of stored energy, or a structural material (some serve as more than one):

a. cellulose

b. sucrose, table sugar

c. glycogen

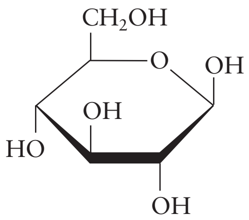
d. starch

17.3 What are the structural differences among monosaccharides, disaccharides, and polysaccharides?

17.4 Match the terms *carbohydrate, monosaccharide, disaccharide*, and *polysaccharide* to each of the following (more than one term may fit):

a. table sugar

b.



c. starch

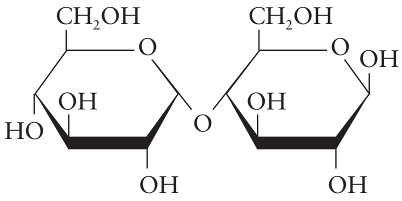
d. glycogen

17.5 Match the terms *carbohydrate, monosaccharide, disaccharide*, and *polysaccharide* to each of the following (more than one term may fit):

a. a. fructose

b. b. cellulose

c.

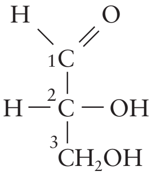


d. amylose

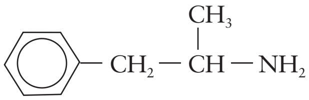
17.6 Define *carbohydrate* in terms of the functional groups present.

The Stereochemistry of Carbohydrates (Section 17.2)

17.7 Why are carbon atoms 1 and 3 of glyceraldehyde not considered chiral?



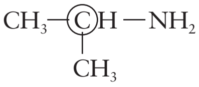
17.8 Locate the chiral carbon in amphetamine and identify the four different groups attached to it.



17.9 Determine whether the circled carbon atoms in each of the following compounds is a chiral center.

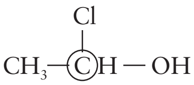
a. $CH_3-\textcircled{C}H_2-OH$

b.



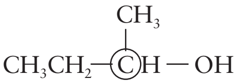
$CH_3-\underset{\underset{CH_3}{|}}{\textcircled{C}}H-NH_2$

c.



$CH_3-\overset{\overset{Cl}{|}}{\textcircled{C}}H-OH$

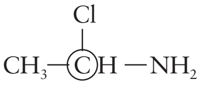
d.



$CH_3CH_2-\overset{\overset{CH_3}{|}}{\textcircled{C}}H-OH$

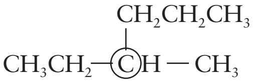
17.10 Determine whether the circled carbon atoms in each of the following compounds is a chiral center.

a.



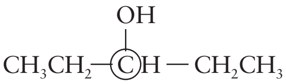
$CH_3-\overset{\overset{Cl}{|}}{\textcircled{C}}H-NH_2$

b.



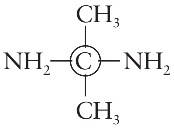
$CH_3CH_2-\overset{\overset{CH_2CH_2CH_3}{|}}{\textcircled{C}}H-CH_3$

c.



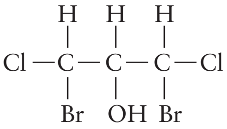
$CH_3CH_2-\overset{\overset{OH}{|}}{\textcircled{C}}H-CH_2CH_3$

d.



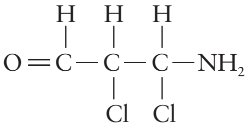
$NH_2-\overset{\overset{CH_3}{|}}{\underset{\underset{CH_3}{|}}{\textcircled{C}}}-NH_2$

17.11 Determine the number of chiral carbon atoms in the following compound, and then calculate the number of stereoisomers possible for the compound.



$Cl-\overset{\overset{H}{|}}{\underset{\underset{Br}{|}}{C}}-\overset{\overset{H}{|}}{\underset{\underset{OH}{|}}{C}}-\overset{\overset{H}{|}}{\underset{\underset{Br}{|}}{C}}-Cl$

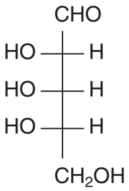
17.12 Determine the number of chiral carbon atoms in the following compound, and then calculate the number of stereoisomers possible for the compound.



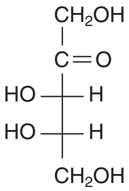
$O=\overset{\overset{H}{|}}{C}-\overset{\overset{H}{|}}{\underset{\underset{Cl}{|}}{C}}-\overset{\overset{H}{|}}{\underset{\underset{Cl}{|}}{C}}-NH_2$

17.13 Draw the Fischer projection of the enantiomer for each of the following compounds:

a.

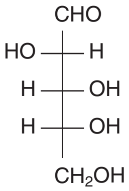


b.

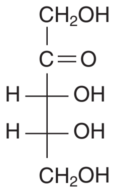


17.14 Draw the Fischer projection of the enantiomer for each of the following compounds:

a.

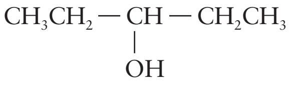


b.



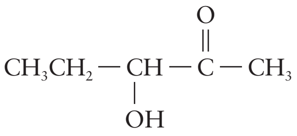
17.15 Which of the following molecules can have enantiomers? Identify any chiral carbon atoms.

a.



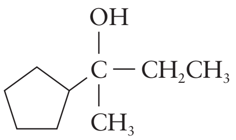
$CH_3CH_2-\underset{OH}{CH}-CH_2CH_3$

b.



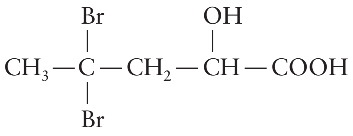
$CH_3CH_2-\underset{OH}{CH}-\overset{O}{\overset{\|}{C}}-CH_3$

c.



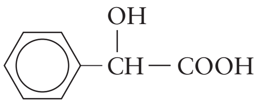
17.16* Which of the following molecules can have enantiomers? Identify any chiral carbon atoms.

a.

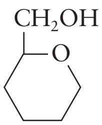


$CH_3-\overset{Br}{\underset{Br}{C}}-CH_2-\overset{OH}{CH}-COOH$

b.

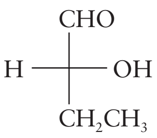


c.



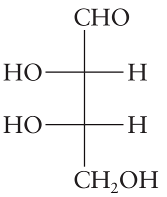
Fischer Projections (Section 17.3)

17.17 Explain what the following Fischer projection denotes about the three-dimensional structure of the compound:

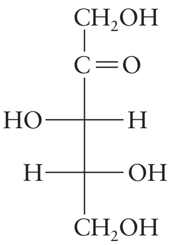


17.18 Identify each of the following as a D or an L form and draw the structural formula of the enantiomer:

a.

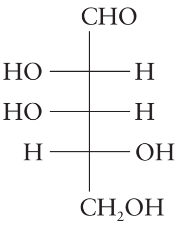


b.

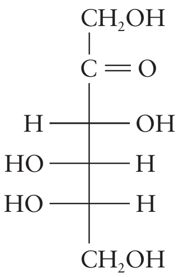


17.19 Identify each of the following as a D or an L form and draw the structural formula of the enantiomer:

a.



b.



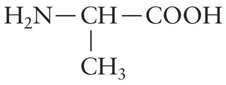
17.20* Draw Fischer projections for both the D and L isomers of the following:

a. 2,3-dihydroxypropanoic acid

b. 2-chloro-3-hydroxypropanoic acid

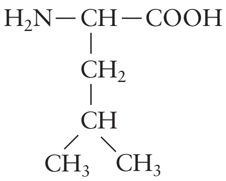
17.21* Draw Fischer projections for both the D and L isomers of the following amino acids:

a. Alanine,



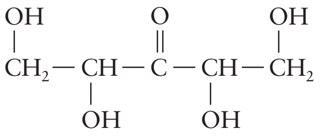
$H_2N-\underset{CH_3}{CH}-COOH$

b. Leucine,



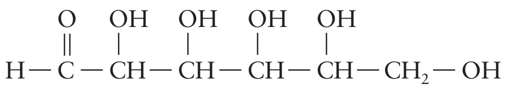
17.22 How many chiral carbon atoms are there in each of the following sugars? How many stereoisomers exist for each compound?

a.



$\overset{OH}{CH_2}-\underset{OH}{CH}-\overset{O}{\overset{\|}{C}}-\underset{OH}{CH}-\overset{OH}{CH_2}$

b.

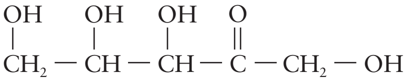


$H-\overset{O}{\overset{\|}{C}}-\overset{OH}{CH}-\overset{OH}{CH}-\overset{OH}{CH}-\overset{OH}{CH}-CH_2-OH$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

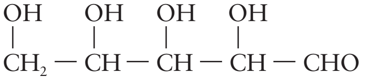
17.23 How many chiral carbon atoms are there in each of the following sugars? How many stereoisomers exist for each compound?

a.



$$\overset{OH}{\overset{|}{CH_2}} - \overset{OH}{\overset{|}{CH}} - \overset{OH}{\overset{|}{CH}} - \overset{O}{\overset{\|}{C}} - CH_2 - OH$$

b.



$$\overset{OH}{\overset{|}{CH_2}} - \overset{OH}{\overset{|}{CH}} - \overset{OH}{\overset{|}{CH}} - \overset{OH}{\overset{|}{CH}} - CHO$$

17.24* How many aldoheptoses are possible? How many are the D form and how many are the L form?

17.25* How many aldopentoses are possible? How many are the D form and how many are the L form?

17.26 Why is the study of chiral molecules important in biochemistry?

17.27 What differences would you expect to see in the following physical properties between (+)-alanine and (–)-alanine?

a. freezing point

b. solubility in an achiral solvent

c. density

d. optical activity

17.28 What differences would you expect to see in the following physical properties between (+)-erythrose and (–)-erythrose?

a. solubility in water

b. melting point

c. effect on plane-polarized light

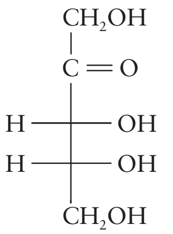
d. boiling point

17.29 What physical property is characteristic of optically active molecules?

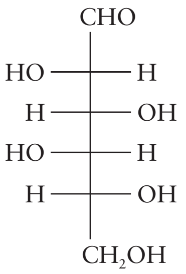
Monosaccharides (Section 17.4)

17.30 Classify each of the following monosaccharides as an aldose or a ketose:

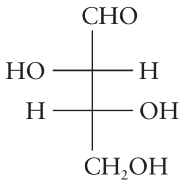
a.



b.

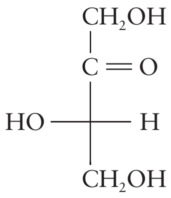


c.

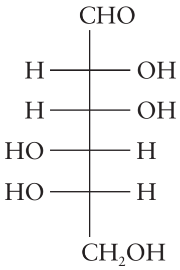


17.31 Classify each of the following monosaccharides as an aldose or a ketose:

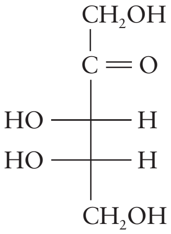
a.



b.



c.

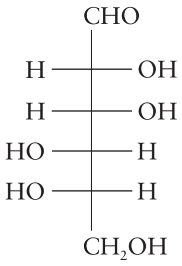


17.32 Classify each monosaccharide in Exercise 17.30 by the number of carbon atoms it has (e.g., tetrose).

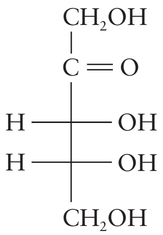
17.33 Classify each monosaccharide in Exercise 17.31 by the number of carbon atoms it has (e.g., tetrose).

17.34 Classify each of the following monosaccharides as an aldo- or keto-triose, tetrose, pentose, or hexose:

a.

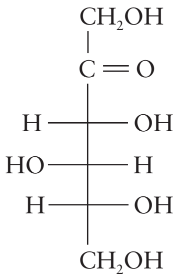


b.

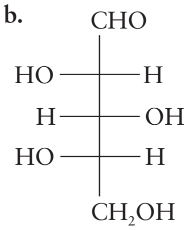


17.35 Classify each of the following monosaccharides as an aldo- or keto-triose, tetrose, pentose, or hexose:

a.



b.



17.36 Draw Fischer projections of any aldotetrose and any ketopentose.

Properties of Monosaccharides (Section 17.5)

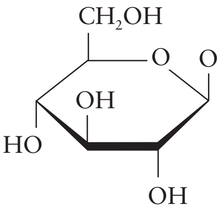
17.37 Explain why certain carbohydrates are called sugars.

17.38 Explain why monosaccharides are soluble in water.

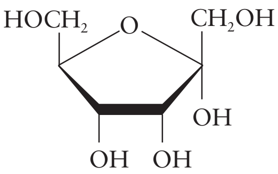
17.39 Using a Fischer projection of a glucose molecule, identify the site(s) on the molecule where water can hydrogen-bond.

17.40 Identify each of the following as an α or a β form and draw the structural formula of the other anomer:

a.

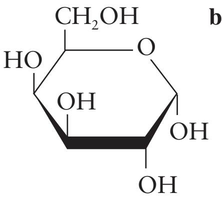

CH₂OH
O
OH
OH
HO
OH

b.

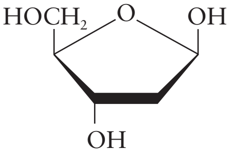

HOCH₂
O
CH₂OH
OH
OH OH

17.41 Identify each of the following as an α or a β form and draw the structural formula of the other anomer:

a.


CH₂OH
O
HO
OH
OH
OH

b.


HOCH₂
O
OH
OH

17.42 The structure of talose differs from galactose only in the direction of the —OH group at position 2. Draw and label Haworth structures for α- and β-talose.

17.43 The structure of mannose differs from glucose only in the direction of the —OH group at position 2. Draw and label Haworth structures for α- and β-mannose.

17.44 What is the difference between pyranose and furanose rings?

17.45 An unknown sugar failed to react with a solution of Cu^{2+}. Classify the compound as a reducing or nonreducing sugar.

17.46 Explain how the cyclic compound β-D-galactose can react with Cu^{2+} and be classified as a reducing sugar.

17.47 Classify each of the following monosaccharides as a *reducing* or *nonreducing* sugar:

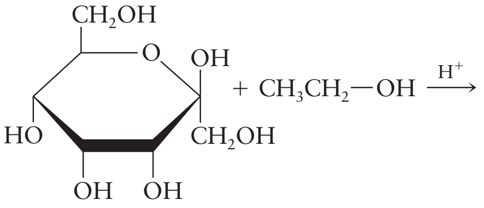
- **a.** D-deoxyribose
- **b.** D-galactose
- **c.** D-glucose
- **d.** D-fructose

17.48 Identify which of the following monosaccharides will give a positive Benedict's test:

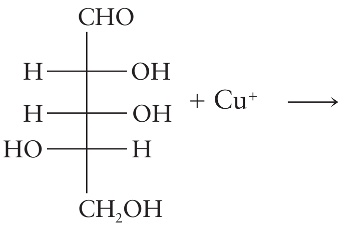
- **a.** D-deoxyribose
- **b.** D-galactose
- **c.** D-glucose
- **d.** D-fructose

17.49 Complete the following reactions:

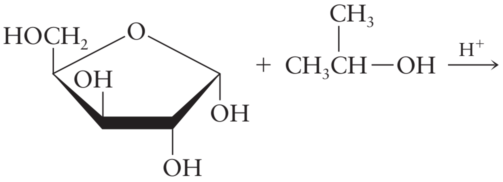
a.


CH₂OH
O
OH
+ CH₃CH₂—OH
H⁺
HO
CH₂OH
OH OH

b.

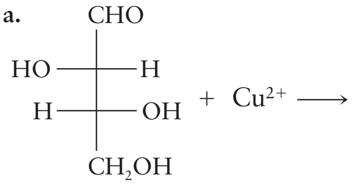

CHO
H
OH
H
OH
HO
H
CH₂OH
+ Cu⁺

c.

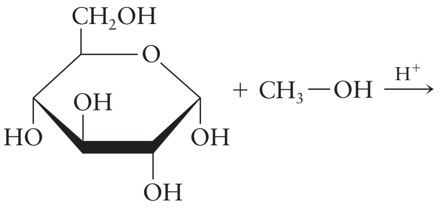

HOCH₂
O
OH
OH
OH
CH₃
+ CH₃CH—OH
H⁺

17.50 Complete the following reactions:

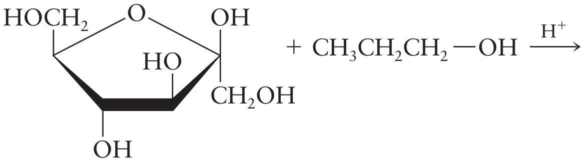
a.


CHO
HO
H
H
OH
CH₂OH
+ Cu²⁺

b.

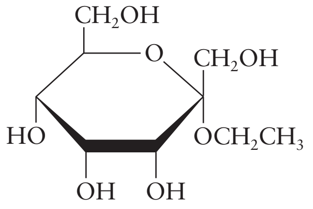

CH₂OH
O
OH
HO
OH
OH
+ CH₃—OH
H⁺

c.

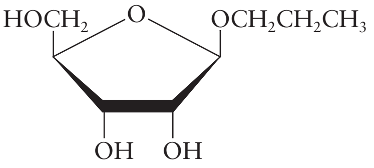

HOCH₂
O
OH
HO
CH₂OH
OH
+ CH₃CH₂CH₂—OH
H⁺

17.51 Use an arrow to identify the glycosidic linkage in each of the following:

a.


CH₂OH
O
CH₂OH
HO
OCH₂CH₃
OH OH

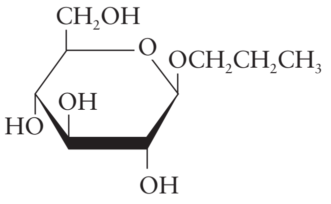
b.


HOCH₂
O
OCH₂CH₂CH₃
OH OH

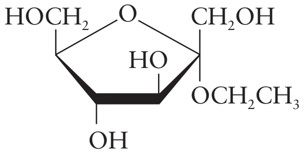
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

17.52 Use an arrow to identify the glycosidic linkage in each of the following:

a.


CH_2OH
O
$OCH_2CH_2CH_3$
OH
HO
OH

b.


$HOCH_2$
O
CH_2OH
HO
OCH_2CH_3
OH

17.53 Draw the structural formula of the alcohol used to make each of the glycosides in Exercise 17.51.

17.54 Draw the structural formula of the alcohol used to make each of the glycosides in Exercise 17.52.

Important Monosaccharides (Section 17.6)

17.55 What monosaccharides are used in the synthesis of nucleic acids?

17.56 Explain why D-glucose can be injected directly into the bloodstream to serve as an energy source.

17.57 Give two other names for D-glucose.

17.58 Which of the following are ketohexoses?

a. glucose **b.** fructose **c.** galactose

17.59 How do the hexoses glucose and galactose differ structurally?

17.60 Give the natural sources for each of the following:

a. glucose **b.** fructose **c.** galactose

17.61 Explain why fructose can be used as a low-calorie sweetener.

Disaccharides (Section 17.7)

17.62 What one monosaccharide is a component of all three of the disaccharides sucrose, maltose, and lactose?

17.63 What monosaccharides are used to make the following disaccharides?

a. sucrose

b. lactose

c. maltose

17.64 Identify a disaccharide that fits each of the following:

a. The most common household sugar

b. Formed during the digestion of starch

c. An ingredient of human milk

d. Found in germinating grain

e. Hydrolyzes when cooked with acidic foods to give invert sugar

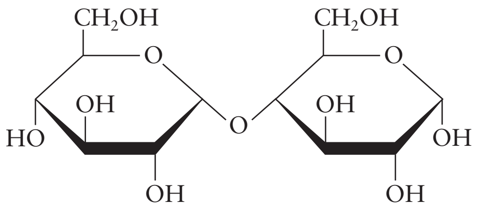
f. Found in high concentrations in sugar cane

17.65 What type of linkage is broken when disaccharides are hydrolyzed to monosaccharides?

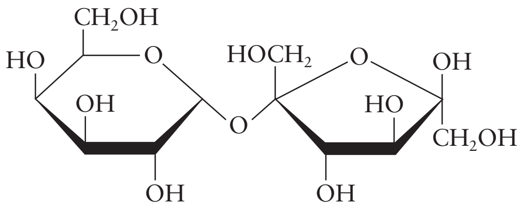
17.66 Explain the process of how the hemiacetal group of a lactose molecule is able to react with Benedict's reagent.

17.67 Identify the monosaccharides present in each of the following disaccharides as glucose, galactose, or fructose:

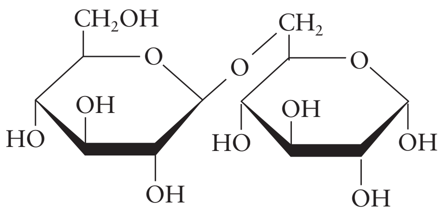
a.


CH_2OH
O
OH
HO
OH
O
CH_2OH
O
OH
OH
OH

b.

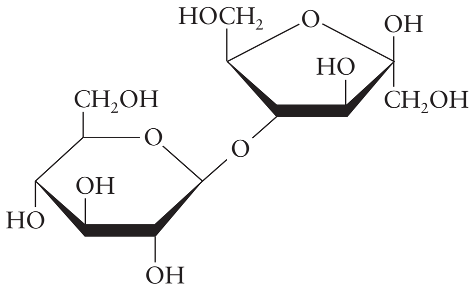

CH_2OH
HO
O
OH
OH
O
$HOCH_2$
O
OH
HO
CH_2OH
OH

c.

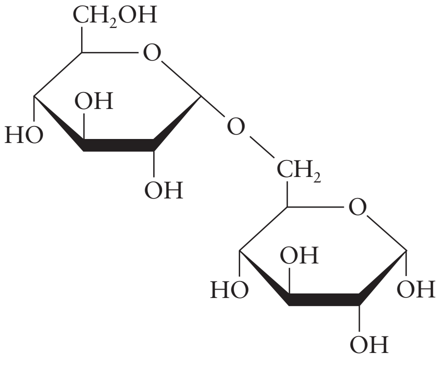

CH_2OH
O
OH
HO
OH
O
CH_2
O
OH
HO
OH
OH

17.68 Identify the monosaccharides present in each of the following disaccharides as glucose, galactose, or fructose:

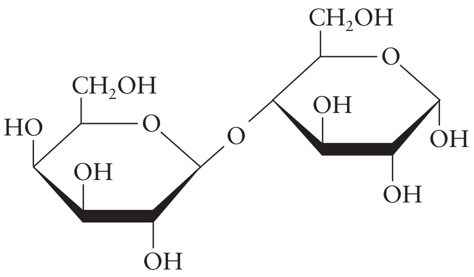
a.


$HOCH_2$
O
OH
HO
CH_2OH
CH_2OH
O
O
OH
HO
OH

b.


CH_2OH
O
OH
HO
OH
O
CH_2
O
OH
HO
OH
OH

c.



17.69 Identify the type of glycosidic linkage (1 → 4, 1 → 5, or 1→6) present in each of the disaccharides in Exercise 17.67.

17.70 Identify the type of glycosidic linkage (1 → 4, 1 → 5, or 1→6) present in each of the disaccharides in Exercise 17.68.

17.71 Identify whether the glycosidic linkages in Exercise 17.67 are in an α or β configuration with respect to the C-1 anomeric carbon.

17.72 Identify whether the glycosidic linkages in Exercise 17.68 are in an α or β configuration with respect to the C-1 anomeric carbon.

17.73 Identify whether each of the disaccharides in Exercise 17.67 gives a positive Benedict's test as a reducing sugar.

17.74 Identify whether each of the disaccharides in Exercise 17.68 gives a positive Benedict's test as a reducing sugar.

17.75 Why is invert sugar sweeter than sucrose?

17.76 Sucrose and honey are commonly used sweeteners. Suppose you had a sweet-tasting water solution that contained either honey or sucrose. How would you chemically determine which sweetener was present?

17.77 Draw Haworth projection formulas of the disaccharides maltose and sucrose. Label the hemiacetal, hemiketal, acetal, or ketal carbons.

17.78 Using structural characteristics, show why

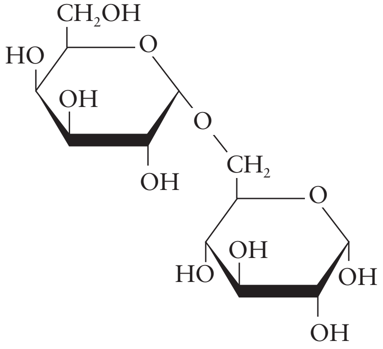
a. lactose is a reducing sugar.

b. sucrose is not a reducing sugar.

17.79 What type of linkage, for example, α(1 → 4), is present in the following?

a. lactose **b.** maltose **c.** sucrose

17.80 The disaccharide melibiose is present in some plant juices.



a. What two monosaccharides are formed on hydrolysis of melibiose?

b. Is melibiose a reducing sugar? Explain.

c. Describe the glycosidic linkage between the two monosaccharide units.

Polysaccharides (Section 17.8)

17.81 Match the following structural characteristics to the polysaccharides amylose, amylopectin, glycogen, and cellulose (a characteristic may fit more than one):

a. Contains both α(1 → 4) and α(1 → 6) glycosidic linkages

b. Is composed of glucose monosaccharide units

c. Contains acetal linkages between monosaccharide units

d. Is composed of highly branched molecular chains

17.82 Match the following structural characteristics to the polysaccharides amylose, amylopectin, glycogen, and cellulose (a characteristic may fit more than one):

a. Is composed of unbranched molecular chains

b. Contains only α(1 → 4) glycosidic linkages

c. Contains only β(1 → 4) glycosidic linkages

d. Has the most α(1 → 6) branching

17.83 Name a polysaccharide that fits each of the following:

a. The unbranched polysaccharide in starch

b. A polysaccharide widely used as a textile fiber

c. The most abundant polysaccharide in starch

d. The primary constituent of paper

e. A storage form of carbohydrates in animals

17.84 List the structural differences and similarities between:

a. glycogen and amylopectin

b. amylose and amylopectin

c. amylose and cellulose

17.85 Polysaccharides are abundant in celery, and yet celery is a good snack for people on a diet. Explain why.

Additional Exercises

17.86 There are two solutions:

(1) a 10% (w/v) water–glucose solution

(2) a 10% (w/v) water–maltose solution

Can you differentiate between the two solutions based on boiling points? Explain your answer.

17.87 Why does one mole of D-glucose only react with one mole of methanol (instead of two) to form an acetal?

17.88 If 100 g of sucrose is completely hydrolyzed to invert sugar, how many grams of glucose will be present?

17.89 Hexanal and 1-hexanol are liquids at room temperature, but glucose (a hexose) is a solid. Give two reasons that may explain this phenomenon.

17.90 Look at **Figure 7.23** in **Section 7.7** showing osmosis through carrot membranes. Suppose maltose was used instead of molasses in the demonstration and the solution level rose 5 cm above the carrot in the tube. Next, maltase, an enzyme that hydrolyzes the glycosidic linkage, was added to the solution. What would happen to the solution level in the tube? Explain your reasoning.

Chemistry for Thought

17.91 Suppose human intestinal bacteria were genetically altered so they could hydrolyze the β linkages of cellulose. Would the results be beneficial? Explain.

17.92 A sample of starch is found to have a molecular weight of 2.80×10^5 u. How many glucose units are present in a molecule of the starch?

17.93 The open-chain form of glucose constitutes only a small fraction of any glucose sample. Yet, when Cu^{2+} is used to oxidize the open-chain form, nearly all the glucose in a sample reacts. Use Le Châtelier's principle to explain this observation.

17.94 Aspartame (Nutrasweet) contains calories and yet is used in diet drinks. Explain how a drink can contain aspartame as a sweetener and yet be low in calories.

17.95 From **Figure 17.13**, what two products form when the lactose in cow's milk is hydrolyzed in a child's digestive system?

17.96 Answer the question raised in **Figure 17.19**. What foods in addition to potatoes would you expect to give a positive starch test?

17.97 Amylopectin is a component of starch, yet it does not give a positive iodine test (turn bluish-black) for the presence of starch when it is tested in its pure form. Why?

17.98 Amylose is a straight-chain glucose polymer similar to cellulose. What would happen to the longevity of paper manufactured with amylose instead of cellulose?

17.99 Raffinose, a trisaccharide found in some plants, contains three monosaccharide components: galactose, glucose, and fructose. Disregarding the types of linkages, how many possible structures are there for raffinose?

18 Lipids

iStock.com/kali9

Health Career Focus

PHYSICAL THERAPY ASSISTANT

My cholesterol was high, and my knee pain excruciating. My doctor said the best way to improve my health was to lose weight. I tried a low-fat diet, but what I really needed was exercise—impossible because my knees hurt so much! Then, my doctor suggested physical therapy.

"I'll give you personalized exercises to build up tiny muscles in your knee joint," explained the physical therapy assistant. By strengthening the knees in this way, I would eventually be able return to walking and hiking—and my weight should improve.

The therapist took all sorts of measurements of my range of motion and strength, then wrote an individualized plan, consisting of surprisingly simple exercises. I "worked out" sitting in a chair, lying on a table, or rode a recumbent bike. It wasn't painful, like I expected. Over time, my strength increased and I could put weight on my knees without pain. The more I moved, the better I felt. Physical therapy changed my life.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Classify lipids as saponifiable or nonsaponifiable and list the major functions of lipids. **(Section 18.1)**
2. Describe four general characteristics of fatty acids. **(Section 18.2)**
3. Draw structural formulas of triglycerides given the formulas of the component parts. **(Section 18.3)**
4. Describe the structural similarities and differences of fats and oils. **(Section 18.3)**
5. Write key reactions for fats and oils. **(Section 18.4)**
6. Compare the structures of fats and waxes. **(Section 18.5)**
7. Draw structural formulas and describe uses for phosphoglycerides. **(Section 18.6)**
8. Draw structural formulas and describe uses for sphingolipids. **(Section 18.7)**
9. Describe the major features of cell membrane structure. **(Section 18.8)**
10. Identify the structural characteristic typical of steroids and list important groups of steroids in the body. **(Section 18.9)**
11. Name the major categories of steroid hormones. **(Section 18.10)**
12. Describe the biological importance and therapeutic uses of the prostaglandins. **(Section 18.11)**

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

THE GROUP OF COMPOUNDS called lipids is made up of substances with widely different compositions and structures. Unlike carbohydrates, which are defined in terms of structure, lipids are defined in terms of a physical property—solubility. Lipids are biological molecules that are insoluble in water but soluble in nonpolar solvents. Lipids are the waxy, greasy, or oily compounds found in plants and animals (see **Figures 18.1** and **18.2**). Lipids repel water, a useful characteristic of protective wax coatings found on some plants. Fats and oils are energy-rich and have relatively low densities. These properties account for their use as storage forms of energy in plants and animals. Still other lipids are used as structural components, especially in the formation of cellular membranes.

Itchy Feet/Shutterstock.com

FIGURE 18.1 Waxes form a protective coating on these leaves.

iStock.com/Mike Matas

FIGURE 18.2 Thick layers of fat help insulate penguins against low temperatures.

18.1 Classification of Lipids

Learning Objective 1 Classify lipids as saponifiable or nonsaponifiable and list the major functions of lipids.

Lipids are grouped into two main classes: saponifiable lipids and nonsaponifiable lipids. Saponification refers to the process in which esters are hydrolyzed under basic conditions (see **Section 15.7**). Triglycerides, waxes, phospholipids, and sphingolipids are esters and thus all belong to the first class. Nonsaponifiable lipids are not esters and cannot be hydrolyzed. Steroids and prostaglandins belong to this class. **Figure 18.3** summarizes the classification of different types of lipids. Notice from the figure that saponifiable lipids are further classified into categories of simple and complex, based on the number of components in their structure. **Simple lipids** contain just two types of components (fatty acids and an alcohol), whereas **complex lipids** contain more than two (fatty acids, an alcohol, plus other components).

lipid A biological compound that is soluble only in nonpolar solvents.

simple lipid An ester-containing lipid with just two types of components: an alcohol and one or more fatty acids.

complex lipid An ester-containing lipid with more than two types of components: an alcohol, fatty acids—plus others.

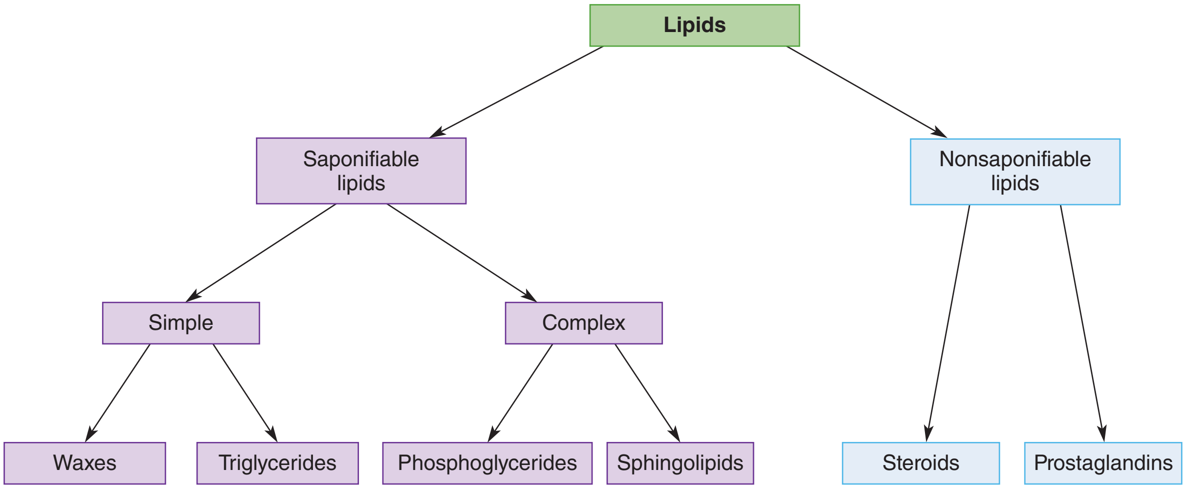

Lipids
Saponifiable lipids
Nonsaponifiable lipids
Simple
Complex
Waxes
Triglycerides
Phosphoglycerides
Sphingolipids
Steroids
Prostaglandins

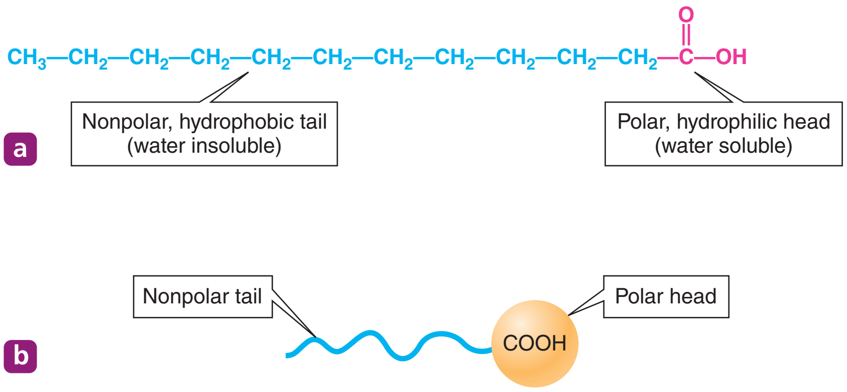
FIGURE 18.3 The major types of lipids.

18.2 Fatty Acids

Learning Objective 2 Describe four general characteristics of fatty acids.

Prior to discussing the chemical structures and properties of the saponifiable lipids, it is useful to first describe the chemistry of fatty acids, the fundamental building blocks of many lipids. Fatty acids (defined in **Section 15.1**) are long-chain carboxylic acids, as shown in **Figure 18.4**. It is the long nonpolar tails of fatty acids that are responsible for most of the fatty or oily characteristics of fats. The carboxyl group, or polar head of fatty acids, is very hydrophilic under conditions of physiological pH, where it exists as the carboxylate anion $—COO^-$.

FIGURE 18.4 The molecular structure of fatty acids: (a) lauric acid and (b) a simplified diagram of a fatty acid with a nonpolar tail and a polar head.


CH3—CH2—CH2—CH2—CH2—CH2—CH2—CH2—CH2—CH2—CH2—C(=O)—OH
a
Nonpolar, hydrophobic tail (water insoluble)
Polar, hydrophilic head (water soluble)
b
Nonpolar tail
Polar head
COOH

In aqueous solution, the ions of fatty acids associate with one another in a rather unique way. The ions form spherical clusters, called **micelles**, in which the nonpolar chains extend toward the interior of the structure away from water, and the polar carboxylate groups face outward in contact with the water. Some micelles are large on a molecular scale and contain hundreds or even thousands of fatty acid molecules. The nonpolar chains in a micelle are held together by weak dispersion forces. The structure of a micelle in a radial cross section is shown in **Figure 18.5**. Micelle formation and structure are important in a number of biological functions, such as the transport of insoluble lipids in the blood (see **Section 24.1**).

micelle A spherical cluster of molecules in which the polar portions of the molecules are on the surface and the nonpolar portions are located in the interior.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

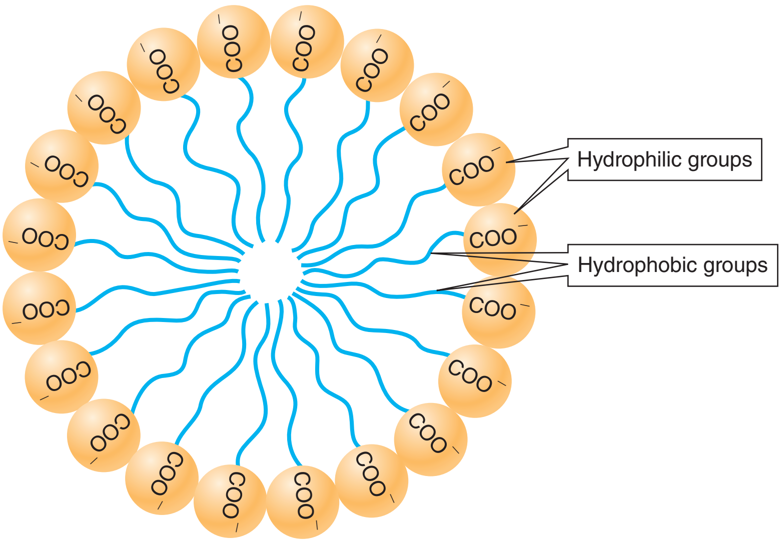
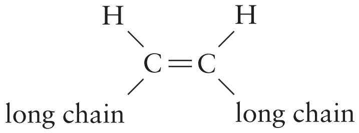


FIGURE 18.5 A cross section of a fatty acid micelle.

The fatty acids found in natural lipids have several characteristics in common:

1. They are usually straight-chain carboxylic acids (no branching).
2. The sizes of most common fatty acids range from 10 to 20 carbons.
3. Fatty acids usually have an even number of carbon atoms (including the carboxyl group carbon).
4. Fatty acids can be saturated (containing no double bonds between carbons) or unsaturated (containing one or more double bonds between carbons). Apart from the carboxyl group and double bonds, there are usually no other functional groups present.

Table 18.1 lists some important fatty acids, along with their formulas and melting points. Unsaturated fatty acids usually contain double bonds in the *cis* configuration.



This configuration creates a long characteristic bend, or kink in the fatty acid chain that is not found in saturated fatty acids.

These kinks prevent unsaturated fatty acid chains from packing together as closely as do the chains of saturated acids (see **Figure 18.6**). As a result, the intermolecular forces are weaker, and unsaturated fatty acids have lower melting points and are usually liquids at room temperature. For example, the melting point of stearic acid (18 carbons) is 71°C, whereas that of oleic acid (18 carbons with one *cis* double bond) is 13°C. The melting point of linoleic acid (18 carbons and two double bonds) is even lower (−5°C). Chain length also affects the melting point, as illustrated by the fact that palmitic acid (16 carbons) melts at 7°C lower than stearic acid (18 carbons). The presence of double bonds and the length of fatty acid chains in membrane lipids partly explain the fluidity of biological membranes, an important feature discussed in **Section 18.8**.

The human body can synthesize all except two of the fatty acids it needs. These two, linoleic acid and linolenic acid, are polyunsaturated fatty acids that contain 18 carbon atoms (see **Table 18.1**). Because they are not synthesized within the body and must be obtained from the diet, they are called **essential fatty acids**. Both are widely distributed in plant and fish oils. In the body, both acids are used to produce hormonelike substances that regulate a wide range of functions and characteristics, including blood pressure, blood clotting, blood lipid levels, the immune response, and the inflammation response to injury and infection.

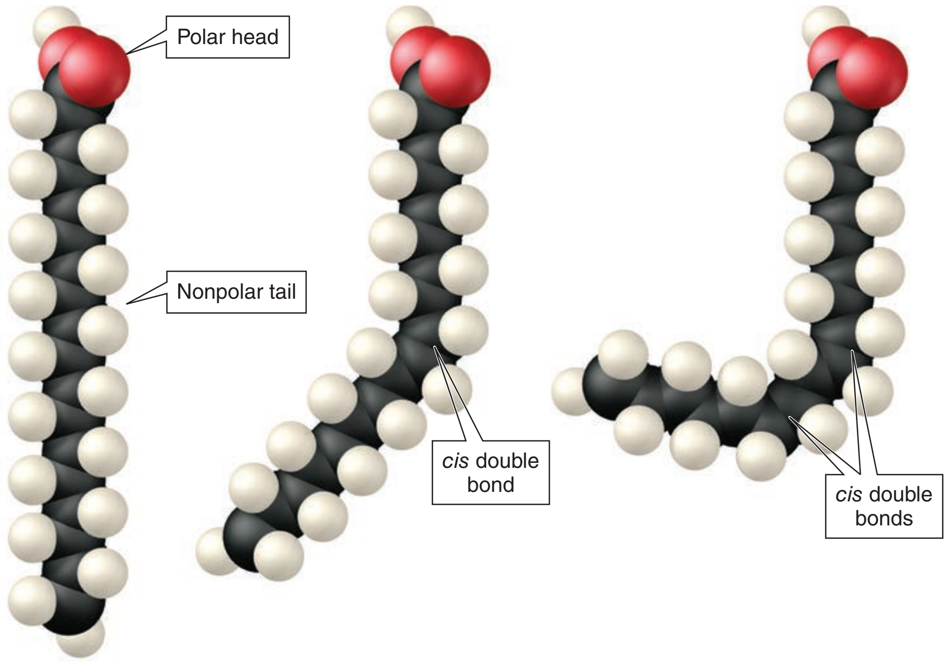
essential fatty acid A fatty acid needed by the body but not synthesized within the body.

TABLE 18.1 Some Important Fatty Acids

Compound Type and Number of Carbons	Name	Formula	Melting Point (°C)	Common Sources
Saturated				
14	Myristic acid	$CH_3(CH_2)_{12}{-}COOH$	54	Butterfat, coconut oil, nutmeg oil
16	Palmitic acid	$CH_3(CH_2)_{14}{-}COOH$	63	Lard, beef fat, butterfat, cottonseed oil
18	Stearic acid	$CH_3(CH_2)_{16}{-}COOH$	70	Lard, beef fat, butterfat, cottonseed oil
20	Arachidic acid	$CH_3(CH_2)_{18}{-}COOH$	76	Peanut oil
Monounsaturated				
16	Palmitoleic acid	$CH_3(CH_2)_5CH{=}CH(CH_2)_7{-}COOH$	−1	Cod liver oil, butterfat
18	Oleic acid	$CH_3(CH_2)_7CH{=}CH(CH_2)_7{-}COOH$	13	Lard, beef fat, olive oil, peanut oil
Polyunsaturated				
18	Linoleic acid[a]	$CH_3(CH_2)_4(CH{=}CHCH_2)_2(CH_2)_6{-}COOH$	−5	Cottonseed oil, soybean oil, corn oil, linseed oil
18	Linolenic acid[b]	$CH_3CH_2(CH{=}CHCH_2)_3(CH_2)_6{-}COOH$	−11	Linseed oil, corn oil
20	Arachidonic acid[a]	$CH_3(CH_2)_4(CH{=}CHCH_2)_4(CH_2)_2{-}COOH$	−50	Corn oil, linseed oil, animal tissues
20	Eicosapentaenoic acid[b]	$CH_3CH_2(CH{=}CHCH_2)_5(CH_2)_2{-}COOH$	−54	Fish oil, seafoods
22	Docosahexaenoic acid[b]	$CH_3CH_2(CH{=}CHCH_2)_6CH_2{-}COOH$	−44	Fish oil, seafoods

[a] Omega-6 fatty acid.

[b] Omega-3 fatty acid.



Stearic Acid
(melting point 71°C)

Oleic Acid
(melting point 13°C)

Linoleic Acid
(melting point –5°C)

FIGURE 18.6 Space-filling models of fatty acids. Unsaturated fatty acids do not pack as tightly as saturated acids, and their melting points are lower than those of saturated acids.

Example 18.1 Fatty Acids

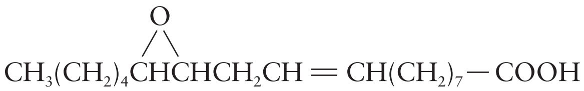
Place each of the following fatty acids into one of three categories: saturated, monounsaturated, or polyunsaturated. State whether each fatty acid is expected to be a solid or liquid at room temperature.

a. $\mathrm{CH_3(CH_2)_3CH{=}CHCH_2CH{=}CH(CH_2)_6{-}COOH}$
b. $\mathrm{CH_3(CH_2)_8{-}COOH}$
c. $\mathrm{CH_3(CH_2)_6CH{=}CH(CH_2)_4{-}COOH}$

Solution

a. The presence of two double bonds means that this is a polyunsaturated fatty acid. Polyunsaturated fatty acids are liquid at room temperature.
b. With no carbon–carbon double bonds, this is a saturated fatty acid and is solid at room temperature.
c. One carbon–carbon double bond is present; it is a monounsaturated fatty acid and is liquid at room temperature.

✔ **LEARNING CHECK 18.1** Unusual fatty acids are sometimes found in seed oils. Classify vernolic acid as saturated, monounsaturated, or polyunsaturated. Further classify it as a solid or liquid at room temperature.



$$\mathrm{CH_3(CH_2)_4\overbrace{CHCH}^{O}CH_2CH{=}CH(CH_2)_7{-}COOH}$$

Linolenic acid is called an omega-3 fatty acid, which means that the endmost double bond is three carbons from the methyl end of the chain:

$$\mathrm{CH_3{-}CH_2{-}(CH{=}CHCH_2)_3{-}(CH_2)_6{-}COOH}$$

linolenic acid

In linoleic acid, an omega-6 fatty acid, the endmost double bond is located six carbons from the methyl end of the chain. Both linoleic and linolenic acids can be converted to other omega-3 and omega-6 fatty acids.

Omega-3 fatty acids have been a topic of interest in medicine since 1985. In that year, researchers reported the results of a study involving natives of Greenland. These individuals have a very low death rate from heart disease, even though their diet is very high in fat. Studies led researchers to conclude that the abundance of fish (see **Figure 18.7**) in the diet of the Greenland natives was involved. Continuing studies led to a possible involvement of the omega-3 fatty acids in the oil of the fish, which may decrease serum cholesterol and triglyceride levels.

A recent 5-year study on the benefits of omega-3 fatty acids involved 18,000 patients with unhealthy cholesterol levels. At the end of the study, patients receiving omega-3 fatty acids had superior cardiovascular function, and nonfatal coronary events were significantly reduced.

Beat J Korner/Shutterstock.com

FIGURE 18.7 Salmon and other cold water fish are excellent sources of omega-3 fatty acids.

Example 18.2 More Classifying Fatty Acids

Identify the following fatty acid as an omega-3 or omega-6 fatty acid:

$$\mathrm{CH_3CH_2(CH{=}CHCH_2)_3(CH_2)_6{-}COOH}$$

Solution

Counting carbons from the terminal $\mathrm{{-}CH_3}$ group, carbon 3 is part of a double bond, making this an omega-3 fatty acid.

✔ **LEARNING CHECK 18.2** Identify the following fatty acid as an omega-3 or omega-6 fatty acid.

$$\mathrm{CH_3(CH_2)_4(CH{=}CHCH_2)_4(CH_2)_2{-}COOH}$$

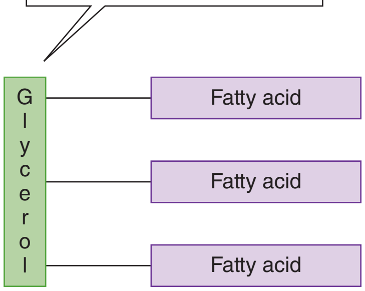
18.3 The Structure of Fats and Oils

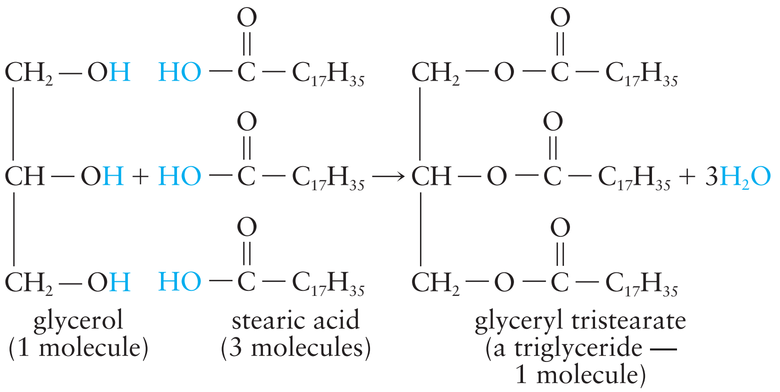
Learning Objective 3 Draw structural formulas of triglycerides and give the formulas of the component parts.

Learning Objective 4 Describe the structural similarities and differences of fats and oils.

Animal fats and vegetable oils are the most widely occurring lipids. Chemically, fats and oils are both esters, and as we learned in **Chapter 15**, esters consist of an alcohol portion and an acid portion. In fats and oils, the alcohol portion is always derived from glycerol, and the acid portion is furnished by fatty acids. Because glycerol has three —OH groups, a single molecule of glycerol can be attached to three different acid molecules. An example is the esterification reaction of stearic acid and glycerol:

The following diagram may help you remember the components of a triglyceride.





$$\begin{array}{lll}
\mathrm{CH_2{-}OH} & \mathrm{HO{-}\overset{O}{\overset{\|}{C}}{-}C_{17}H_{35}} & \mathrm{CH_2{-}O{-}\overset{O}{\overset{\|}{C}}{-}C_{17}H_{35}} \\
| & & | \\
\mathrm{CH{-}OH} \; + & \mathrm{HO{-}\overset{O}{\overset{\|}{C}}{-}C_{17}H_{35}} \longrightarrow & \mathrm{CH{-}O{-}\overset{O}{\overset{\|}{C}}{-}C_{17}H_{35}} + 3H_2O \\
| & & | \\
\mathrm{CH_2{-}OH} & \mathrm{HO{-}\overset{O}{\overset{\|}{C}}{-}C_{17}H_{35}} & \mathrm{CH_2{-}O{-}\overset{O}{\overset{\|}{C}}{-}C_{17}H_{35}}
\end{array} \qquad (18.1)$$

triglyceride or triacylglycerol
A triester of glycerol in which all three alcohol groups are esterified.

The resulting esters are called **triglycerides** or **triacylglycerols**.

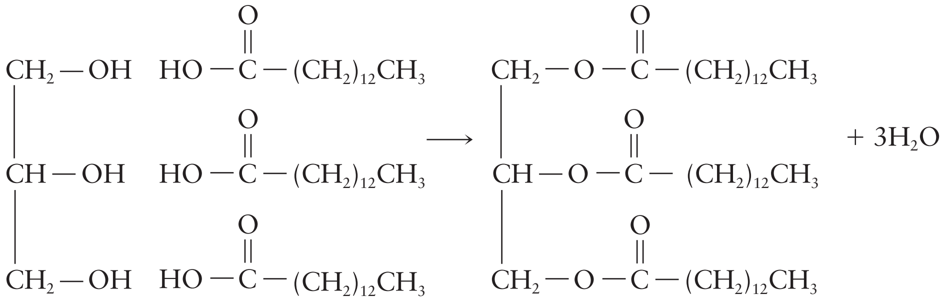
The fatty acid components in naturally occurring triglyceride molecules are rarely identical (as in the case of glyceryl tristearate). In addition, natural triglycerides (fats and oils) are usually mixtures of different triglyceride molecules. Butterfat, for example, contains at least 14 different fatty acid components.

Example 18.3 Writing Structures for Triglycerides

Write the structure for the triglyceride that is formed from glycerol and three molecules of myristic acid.

Solution

Using Reaction 18.1 as a guide, position a molecule of glycerol to the left. Align three molecules of myristic acid (see **Table 18.1**). Finally, eliminate water molecules to form the three ester linkages.



$$\begin{array}{lll}
\mathrm{CH_2{-}OH} & \mathrm{HO{-}\overset{O}{\overset{\|}{C}}{-}(CH_2)_{12}CH_3} & \mathrm{CH_2{-}O{-}\overset{O}{\overset{\|}{C}}{-}(CH_2)_{12}CH_3} \\
| & & | \\
\mathrm{CH{-}OH} & \mathrm{HO{-}\overset{O}{\overset{\|}{C}}{-}(CH_2)_{12}CH_3} \longrightarrow & \mathrm{CH{-}O{-}\overset{O}{\overset{\|}{C}}{-}(CH_2)_{12}CH_3} \quad + 3H_2O \\
| & & | \\
\mathrm{CH_2{-}OH} & \mathrm{HO{-}\overset{O}{\overset{\|}{C}}{-}(CH_2)_{12}CH_3} & \mathrm{CH_2{-}O{-}\overset{O}{\overset{\|}{C}}{-}(CH_2)_{12}CH_3}
\end{array}$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

✔ **LEARNING CHECK 18.3** Write one structure (several possibilities exist) for a triglyceride derived from stearic acid, oleic acid, and palmitic acid.

With some exceptions, triglycerides that come from animals other than fish are solids at room temperature and are called **fats**. Triglycerides from plants or fish are liquids at room temperature and are usually referred to as **oils**. Although both fats and oils are triglycerides, they differ structurally in one important respect—the degree of unsaturation. As shown in **Figure 18.8**, animal fats contain primarily triglycerides of long-chain saturated fatty acids (higher melting points). In contrast, vegetable oils, such as corn oil and sunflower oil, consist of triglycerides containing unsaturated fatty acids (lower melting points) (see **Figure 18.9**). Thus, we see that the structural and physical properties of fatty acids determine the properties of the triglycerides derived from them.

fat A triglyceride that is solid at room temperature.

oil A triglyceride that is liquid at room temperature.

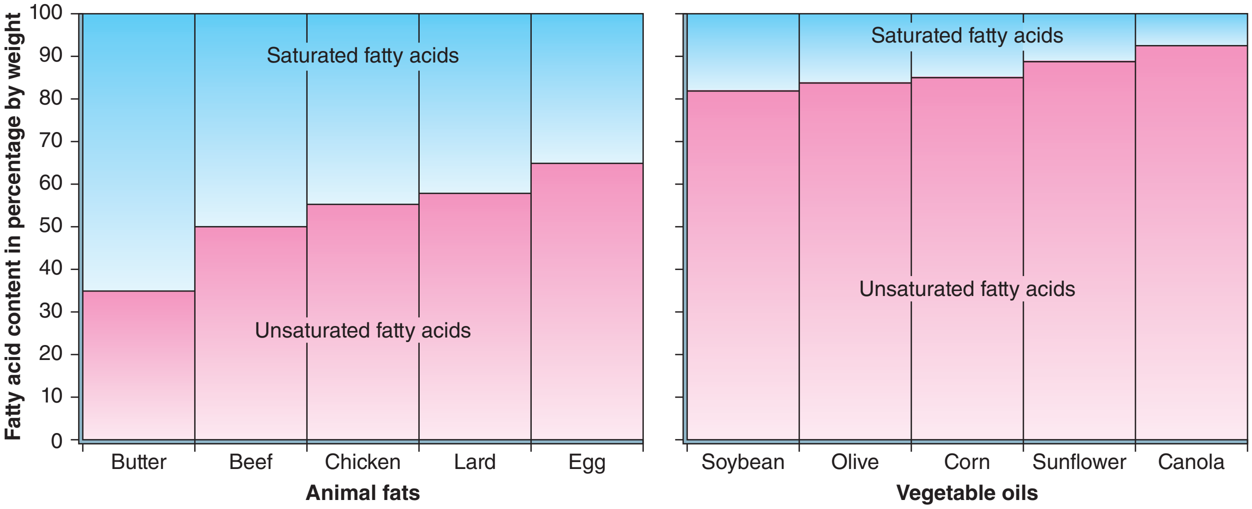


FIGURE 18.8 A comparison of saturated and unsaturated fatty acids in some foods.

© Michael C. Slabaugh

FIGURE 18.9 Sunflowers are an important crop in some regions of the country because the seeds are a good source of unsaturated oils. Why do you think seeds are rich in oils?

Excessive fat in the diet is recognized as one risk factor influencing the development of chronic disease. The main concern about excessive dietary fat, especially saturated fat, centers on its role in raising blood cholesterol levels (see **Section 18.9**). High blood cholesterol is a recognized risk factor in the development of coronary heart disease, the leading cause of death in Americans every year.

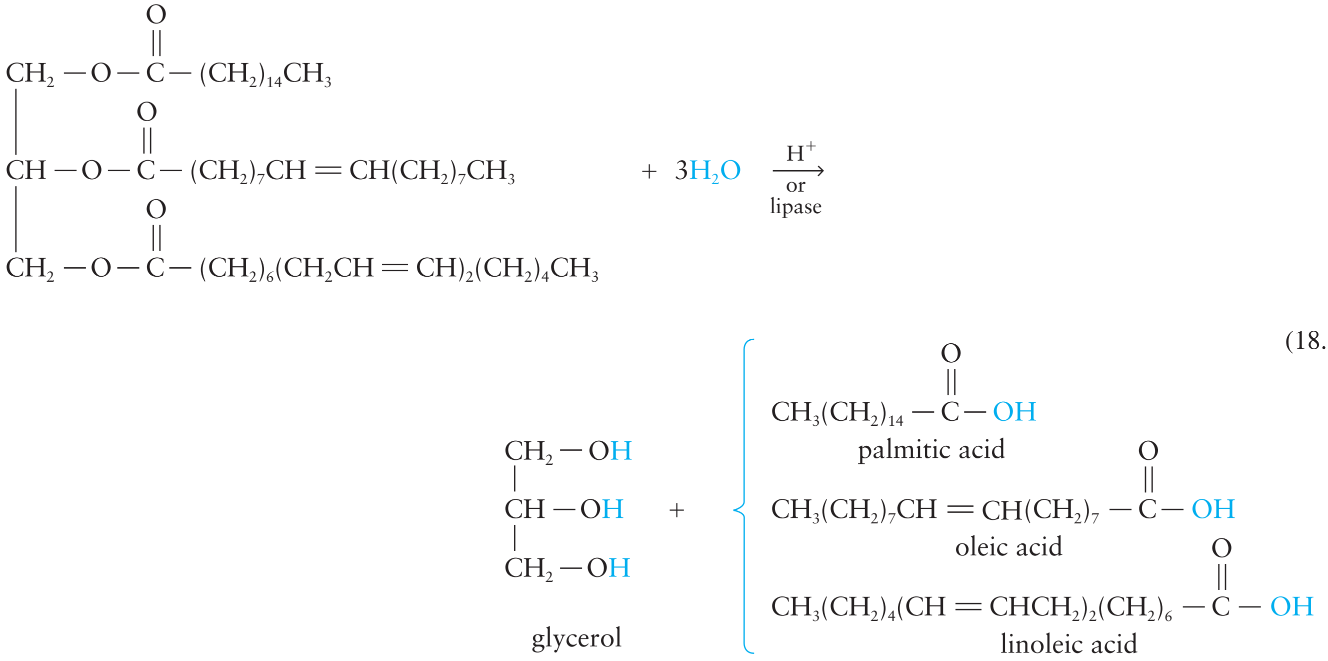
18.4 Chemical Properties of Fats and Oils

Learning Objective 5 Write key reactions for fats and oils.

The chemical properties of triglycerides are typical of esters and alkenes because these are the two functional groups present.

18.4A Hydrolysis

Hydrolysis is one of the most important reactions of fats and oils, just as it was for carbohydrates. The treatment of fats or oils with water and an acid catalyst causes them to hydrolyze to form glycerol and fatty acids. This reaction is simply the reverse of ester formation:



$$\begin{array}{l} CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_{14}CH_3 \\ | \\ CH-O-\overset{O}{\overset{\|}{C}}-(CH_2)_7CH=CH(CH_2)_7CH_3 \\ | \\ CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_6(CH_2CH=CH)_2(CH_2)_4CH_3 \end{array} + 3H_2O \xrightarrow[\text{or lipase}]{H^+}$$

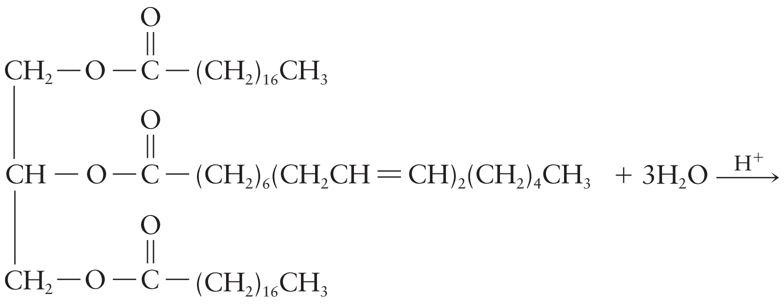
(18.2)

$$\underset{\text{glycerol}}{\begin{array}{l} CH_2-OH \\ | \\ CH-OH \\ | \\ CH_2-OH \end{array}} + \left\{ \begin{array}{l} \underset{\text{palmitic acid}}{CH_3(CH_2)_{14}-\overset{O}{\overset{\|}{C}}-OH} \\ \underset{\text{oleic acid}}{CH_3(CH_2)_7CH=CH(CH_2)_7-\overset{O}{\overset{\|}{C}}-OH} \\ \underset{\text{linoleic acid}}{CH_3(CH_2)_4(CH=CHCH_2)_2(CH_2)_6-\overset{O}{\overset{\|}{C}}-OH} \end{array} \right.$$

Enzymes (lipases) of the digestive system also catalyze the hydrolysis process. This reaction represents the only important change that takes place in fats and oils during digestion. The breakdown of cellular fat deposits to supply energy also begins with the lipase-catalyzed hydrolysis reaction.

Example 18.4 Writing Hydrolysis Reactions

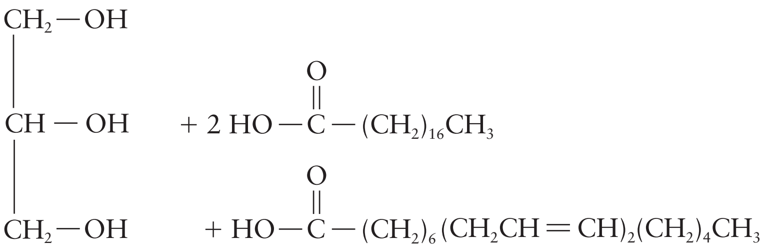
Write the structure of the hydrolysis products of the following reaction:



$$\begin{array}{l} CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_{16}CH_3 \\ | \\ CH-O-\overset{O}{\overset{\|}{C}}-(CH_2)_6(CH_2CH=CH)_2(CH_2)_4CH_3 \\ | \\ CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_{16}CH_3 \end{array} + 3H_2O \xrightarrow{H^+}$$

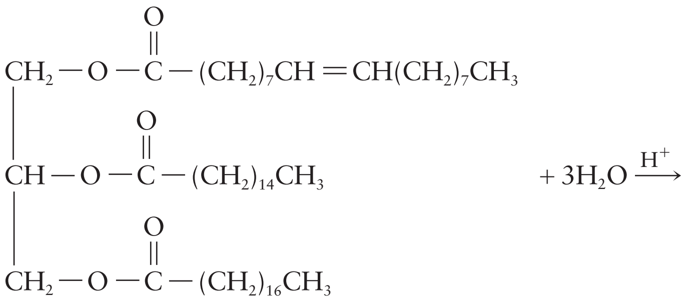
Solution

Using Reaction 18.2 as a guide, the products will be glycerol and three molecules of fatty acid. In this case, two fatty acid molecules are identical.



$$\begin{array}{l} CH_2-OH \\ | \\ CH-OH \\ | \\ CH_2-OH \end{array} \begin{array}{l} + 2\,HO-\overset{O}{\overset{\|}{C}}-(CH_2)_{16}CH_3 \\ + HO-\overset{O}{\overset{\|}{C}}-(CH_2)_6(CH_2CH=CH)_2(CH_2)_4CH_3 \end{array}$$

✔ LEARNING CHECK 18.4 Write the structures of the hydrolysis products of the following reaction:

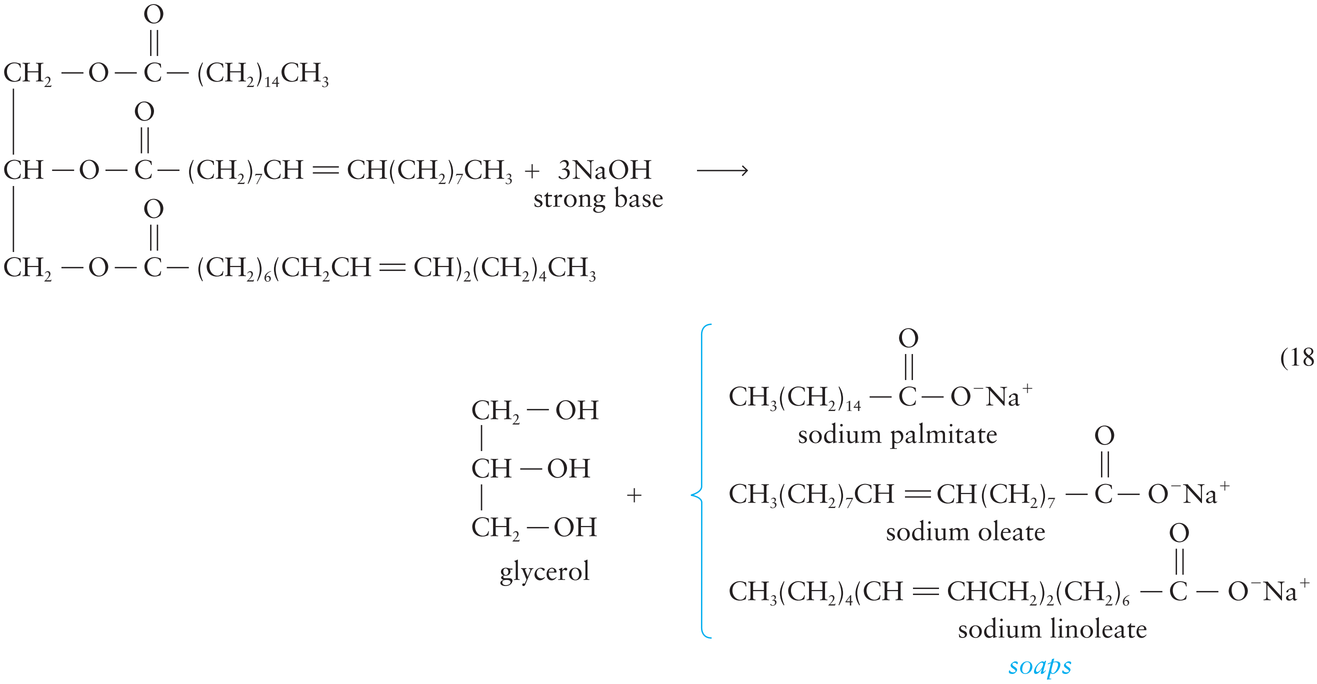


$$\begin{array}{l} CH_2-O-\overset{\overset{\displaystyle O}{\|}}{C}-(CH_2)_7CH=CH(CH_2)_7CH_3 \\ | \\ CH-O-\overset{\overset{\displaystyle O}{\|}}{C}-(CH_2)_{14}CH_3 \qquad\qquad + 3H_2O \xrightarrow{H^+} \\ | \\ CH_2-O-\overset{\overset{\displaystyle O}{\|}}{C}-(CH_2)_{16}CH_3 \end{array}$$

18.4B Saponification

When triglycerides are reacted with a strong base, the process of saponification (soap making) occurs. In this commercially important reaction, the products are glycerol and the salts of fatty acids, which are also called **soaps** (Reaction 18.3).

soap A salt of a fatty acid often used as a cleaning agent.



$$\begin{array}{l} CH_2-O-\overset{\overset{\displaystyle O}{\|}}{C}-(CH_2)_{14}CH_3 \\ | \\ CH-O-\overset{\overset{\displaystyle O}{\|}}{C}-(CH_2)_7CH=CH(CH_2)_7CH_3 + \underset{\text{strong base}}{3NaOH} \longrightarrow \\ | \\ CH_2-O-\overset{\overset{\displaystyle O}{\|}}{C}-(CH_2)_6(CH_2CH=CH)_2(CH_2)_4CH_3 \end{array}$$

$$\underset{\text{glycerol}}{\begin{array}{l} CH_2-OH \\ | \\ CH-OH \\ | \\ CH_2-OH \end{array}} + \underset{\textit{soaps}}{\left\{ \begin{array}{l} CH_3(CH_2)_{14}-\overset{\overset{\displaystyle O}{\|}}{C}-O^-Na^+ \quad \text{sodium palmitate} \\ CH_3(CH_2)_7CH=CH(CH_2)_7-\overset{\overset{\displaystyle O}{\|}}{C}-O^-Na^+ \quad \text{sodium oleate} \\ CH_3(CH_2)_4(CH=CHCH_2)_2(CH_2)_6-\overset{\overset{\displaystyle O}{\|}}{C}-O^-Na^+ \quad \text{sodium linoleate} \end{array} \right.}$$

(18.3)

The salts obtained from saponification depend on the base used. Sodium salts, known as hard soaps (see **Figure 18.10**), are found in most cake soap used in the home. Potassium salts, known as soft soaps, are used in some shaving creams and liquid soap preparations.

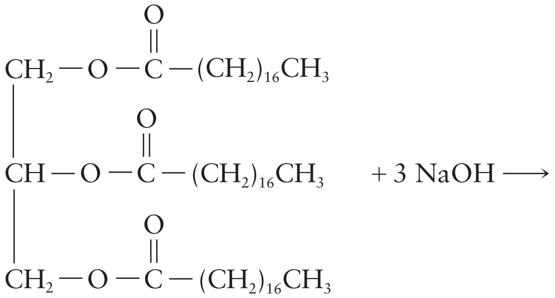
In traditional soap making, animal fat is the source of triglycerides, and lye (crude NaOH) or an aqueous extract of wood ashes is the source of the base. The importance of soap making was amply proved after the soap maker's art was lost with the fall of the Roman Empire. The soapless centuries between 500–1500 A.D. were notorious for the devastating plagues that nearly depopulated an unsanitary western Europe.

iStock.com/kali9

FIGURE 18.10 The use of soaps by health professionals is vital in controlling the spread of infectious microorganisms.

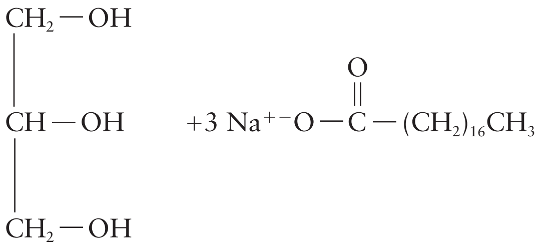
Example 18.5 Writing Saponification Reactions

Write structures for the products formed when the following triglyceride is saponified using NaOH.

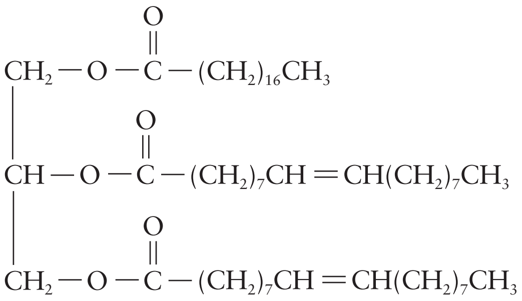


Solution

Following the pattern of Reaction 18.3, the products will be glycerol and three molecules of fatty acid salt. In this case, the three molecules of fatty acid salt are identical.



✔ LEARNING CHECK 18.5 Write structures for the products formed when the following triglyceride is saponified using NaOH:



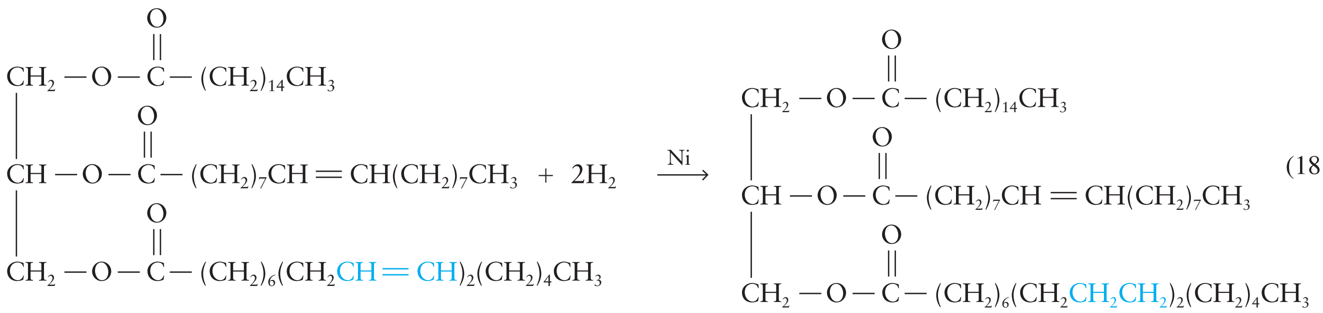
Michael Slabaugh

FIGURE 18.11 Hydrogenation of vegetable oils is used to prepare both shortenings and margarines. How do oils used in automobiles differ chemically from these vegetable oils?

18.4C Hydrogenation

In **Chapter 12**, we learned that double bonds can be reduced to single bonds by treatment with hydrogen (H_2) in the presence of a catalyst. An important commercial reaction of fats and oils uses this same hydrogenation process, in which some of the fatty acid double bonds are converted to single bonds. The result is a decrease in the degree of unsaturation and a corresponding increase in the melting point of the fat or oil (see **Figure 18.6**). The peanut oil in many popular brands of peanut butter has been partially hydrogenated to convert the oil to a semisolid that does not separate. Hydrogenation is most often used in the production of semisolid cooking shortenings (such as Crisco®, and Fluffo®) or margarines from liquid vegetable oils (see **Figure 18.11**).

Partially hydrogenated vegetable oils were developed in part to help displace highly saturated animal fats used in frying, baking, and spreads. It is important not to complete the reaction and totally saturate all the double bonds. If this is done, the product is hard and waxy—not the smooth, creamy product desired by consumers. Equation 18.4 gives an example in which some of the double bonds react, showing one of the possible products.

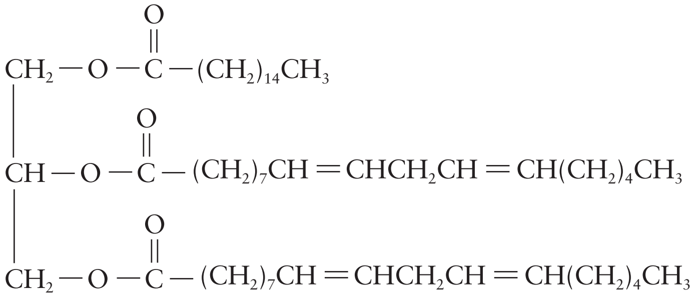


$$\begin{array}{l} CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_{14}CH_3 \\ | \\ CH-O-\overset{O}{\overset{\|}{C}}-(CH_2)_7CH=CH(CH_2)_7CH_3 \\ | \\ CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_6(CH_2CH=CH)_2(CH_2)_4CH_3 \end{array} + 2H_2 \xrightarrow{Ni} \begin{array}{l} CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_{14}CH_3 \\ | \\ CH-O-\overset{O}{\overset{\|}{C}}-(CH_2)_7CH=CH(CH_2)_7CH_3 \\ | \\ CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_6(CH_2CH_2CH_2)_2(CH_2)_4CH_3 \end{array}$$

(18.4)

Example 18.6 Writing Hydrogenation Reactions

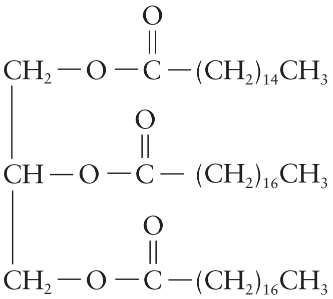
Write the structure of the product formed when the following triglyceride is completely hydrogenated:



$$\begin{array}{l} CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_{14}CH_3 \\ | \\ CH-O-\overset{O}{\overset{\|}{C}}-(CH_2)_7CH=CHCH_2CH=CH(CH_2)_4CH_3 \\ | \\ CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_7CH=CHCH_2CH=CH(CH_2)_4CH_3 \end{array}$$

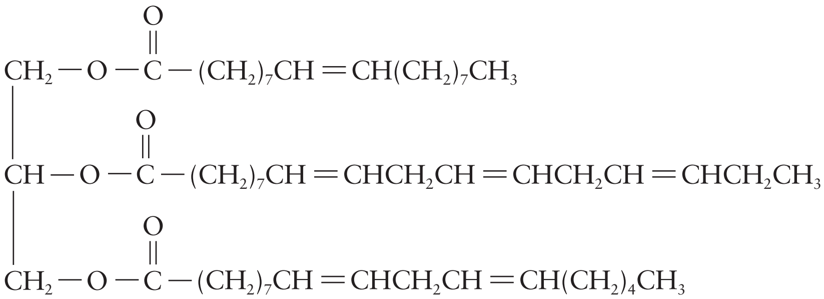
Solution

Using Reaction 18.4 as a guide, the four carbon–carbon double bonds would each react with a molecule of hydrogen, eliminating the double bonds.



$$\begin{array}{l} CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_{14}CH_3 \\ | \\ CH-O-\overset{O}{\overset{\|}{C}}-(CH_2)_{16}CH_3 \\ | \\ CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_{16}CH_3 \end{array}$$

✔ **LEARNING CHECK 18.6** If an oil with the following structure is completely hydrogenated, what is the structure of the product?



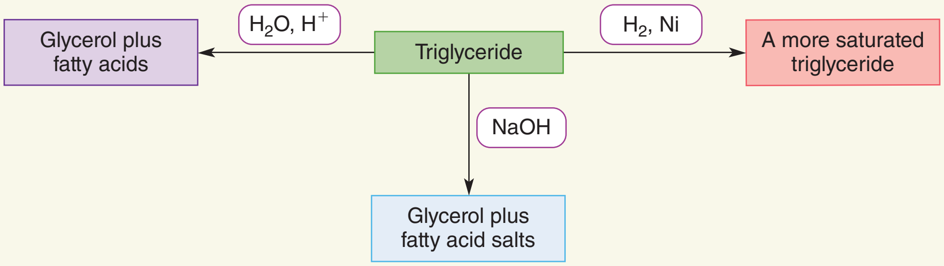
$$\begin{array}{l} CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_7CH=CH(CH_2)_7CH_3 \\ | \\ CH-O-\overset{O}{\overset{\|}{C}}-(CH_2)_7CH=CHCH_2CH=CHCH_2CH=CHCH_2CH_3 \\ | \\ CH_2-O-\overset{O}{\overset{\|}{C}}-(CH_2)_7CH=CHCH_2CH=CH(CH_2)_4CH_3 \end{array}$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STUDY TOOLS 18.1

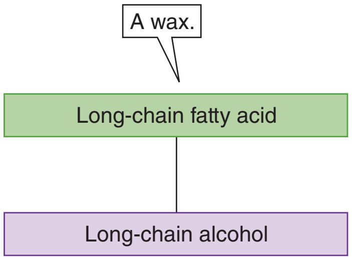
A Reaction Map for Triglycerides

We've discussed three different reactions of triglycerides. Remember, when you're trying to decide what happens in a reaction, focus attention on the functional groups. After identifying a triglyceride as a starting material, then decide what other reagent is involved and which of the three pathways is appropriate.


Glycerol plus fatty acids
H_2O, H^+
Triglyceride
H_2, Ni
A more saturated triglyceride
NaOH
Glycerol plus fatty acid salts

During hydrogenation, some fatty acid molecules in the common *cis* configuration (see **Section 18.2**) are isomerized into *trans* fatty acids. The main sources of *trans* fatty acids in the diet are stick margarine, shortening, and high-fat baked goods. Recent clinical studies have shown that blood cholesterol levels may be raised by the consumption of *trans* fatty acids. Current dietary advice is to reduce the consumption of saturated fatty acids and products that contain significant amounts of *trans* fatty acids. In 2015, the Food and Drug Administration (FDA) took action to eliminate the use of partially hydrogenated oils, the major source of *trans* fatty acids (also called *trans* fats) in the food supply. This action is expected to reduce coronary heart disease and prevent thousands of fatal heart attacks each year in the United States. The World Health Organization (WHO) has called for a worldwide ban of artificial trans fats by 2023.

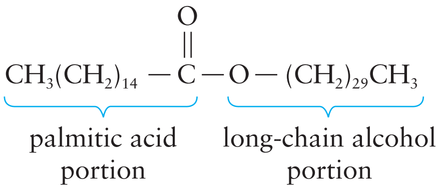
wax An ester of a long-chain fatty acid and a long-chain alcohol.



18.5 Waxes

Learning Objective 6 Compare the structures of fats and waxes.

Waxes represent a second group of simple lipids that, like fats and oils, are esters of fatty acids. However, the alcohol portion of waxes is derived from long-chain alcohols (12–32 carbons) rather than glycerol. Beeswax, for example, contains a wax with the following structure:



$$\underbrace{CH_3(CH_2)_{14}-\overset{\overset{\displaystyle O}{\|}}{C}}_{\text{palmitic acid portion}}\underbrace{-O-(CH_2)_{29}CH_3}_{\text{long-chain alcohol portion}}$$

StudioSmart/Shutterstock.com

FIGURE 18.12 Beeswax is used in lip balm, candles, hand creams, salves, and moisturizers; and in cosmetics such as eye shadow.

Waxes are water insoluble and not as easily hydrolyzed as fats and oils. Consequently, they often occur in nature as protective coatings on feathers, fur, skin, leaves, and fruits. Sebum, a secretion of the sebaceous glands of the skin, contains many different waxes. It keeps the skin soft and prevents dehydration. Waxes are used commercially to make cosmetics, candles, ointments, and protective polishes (see **Figure 18.12**).

phosphoglyceride A complex lipid containing glycerol, fatty acids, phosphoric acid, and an aminoalcohol component.

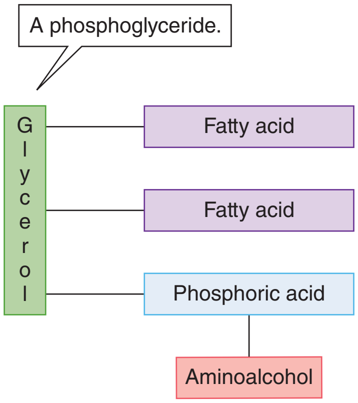
phospholipid A phosphorus-containing lipid.

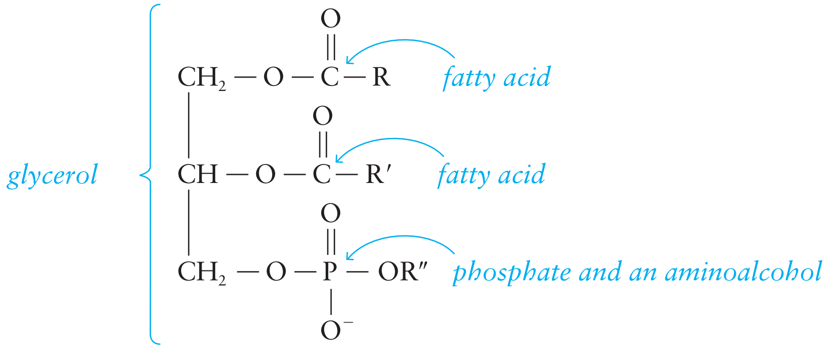
18.6 Phosphoglycerides

Learning Objective 7 Draw structural formulas and describe uses for phosphoglycerides.

Phosphoglycerides are complex lipids that serve as the major components of cell membranes. Phosphoglycerides and related compounds are also referred to as **phospholipids**.

In these compounds, one of the —OH groups of glycerol is joined by an ester linkage to phosphoric acid, which in turn is linked to another alcohol (usually an aminoalcohol). The other two —OH groups of glycerol are linked to fatty acids, resulting in the following general structure:

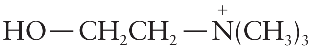




$$\begin{array}{l} CH_2-O-\overset{\displaystyle O}{\overset{\|}{C}}-R \\ | \\ CH-O-\overset{\displaystyle O}{\overset{\|}{C}}-R' \\ | \\ CH_2-O-\underset{\displaystyle O^-}{\underset{|}{\overset{\displaystyle O}{\overset{\|}{P}}}}-OR'' \end{array}$$

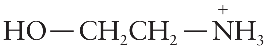
a phosphoglyceride

The most abundant phosphoglycerides have one of the alcohols choline, ethanolamine, or serine attached to the phosphate group. These aminoalcohols are shown below in charged forms:



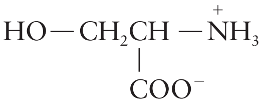
$$HO-CH_2CH_2-\overset{+}{N}(CH_3)_3$$

choline
(a quaternary
ammonium cation)



$$HO-CH_2CH_2-\overset{+}{N}H_3$$

ethanolamine
(cation form)

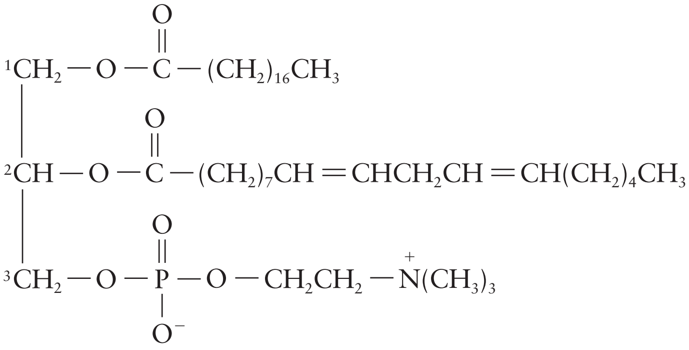


$$HO-CH_2\underset{\displaystyle COO^-}{\underset{|}{CH}}-\overset{+}{N}H_3$$

serine
(two ionic groups
present)

A typical phosphoglyceride is phosphatidylcholine, which is commonly called **lecithin**:

lecithin A phosphoglyceride containing choline.



$$\begin{array}{l} {}^1CH_2-O-\overset{\displaystyle O}{\overset{\|}{C}}-(CH_2)_{16}CH_3 \\ | \\ {}^2CH-O-\overset{\displaystyle O}{\overset{\|}{C}}-(CH_2)_7CH=CHCH_2CH=CH(CH_2)_4CH_3 \\ | \\ {}^3CH_2-O-\underset{\displaystyle O^-}{\underset{|}{\overset{\displaystyle O}{\overset{\|}{P}}}}-O-CH_2CH_2-\overset{+}{N}(CH_3)_3 \end{array}$$

phosphatidylcholine

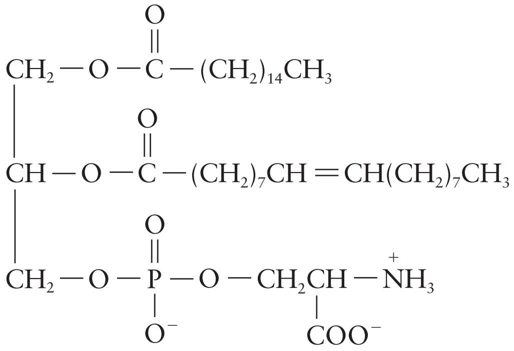
All phosphoglycerides that contain choline are classified as lecithins. Because different fatty acids may be bonded at positions 1 and 2 of the glycerol, a number of different lecithins are possible. Note that the lecithin shown contains a negatively charged phosphate group and a positively charged quaternary nitrogen. These charges make that end of the molecule strongly hydrophilic, whereas the rest of the molecule is hydrophobic. This structure of lecithins enables them to function as very important structural components of most cell membranes (see **Section 18.8**). It also allows lecithins to function as emulsifying and micelle-forming agents. Such micelles play an important role in the transport of lipids in the blood (see **Chapter 24**). Lecithin (phosphatidylcholine) is commercially extracted from soybeans for use as an emulsifying agent in food. It gives a smooth texture to such products as margarine and chocolate candies (see **Figure 18.13**).

© Maren Slabaugh

FIGURE 18.13 Some common foods containing lecithins as emulsifying agents.

cephalin A phosphoglyceride containing ethanolamine or serine.

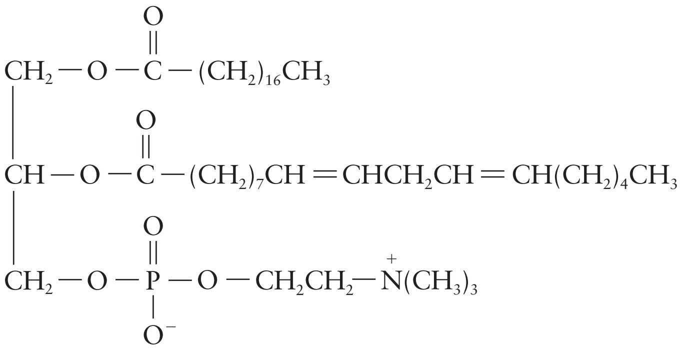
Phosphoglycerides in which the alcohol is ethanolamine or serine, rather than choline, are called **cephalins**. They are found in most cell membranes and are particularly abundant in brain tissue. Cephalins are also found in blood platelets, where they play an important role in the blood-clotting process. A typical cephalin is represented as:


$$\begin{array}{l} \mathrm{CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{14}CH_3} \\ | \\ \mathrm{CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_7CH=CH(CH_2)_7CH_3} \\ | \\ \mathrm{CH_2-O-\underset{\underset{O^-}{|}}{\overset{\overset{O}{\|}}{P}}-O-CH_2\underset{\underset{COO^-}{|}}{CH}-\overset{+}{N}H_3} \end{array}$$

Note the presence of the negatively charged phosphate and carboxyl groups and positively charged nitrogen. This characteristic allows cephalins, like the lecithins, to function as emulsifiers.

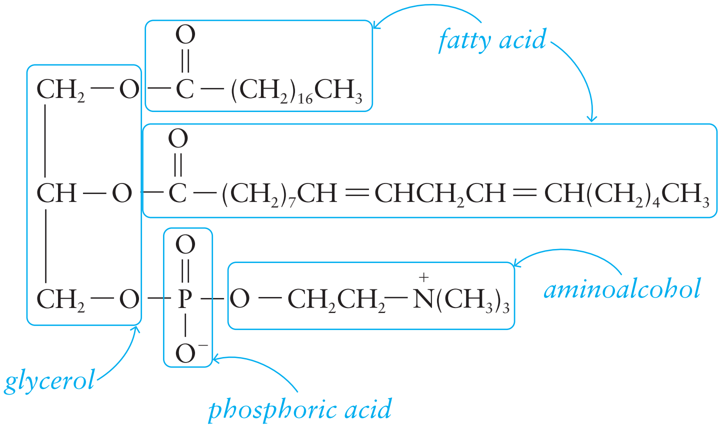
Example 18.7 Writing Phosphoglyceride Structures

In the following phosphoglyceride structure, circle the component parts and label each circle with one of these terms: glycerol, fatty acid, phosphoric acid, or aminoalcohol.


$$\begin{array}{l} \mathrm{CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{16}CH_3} \\ | \\ \mathrm{CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_7CH=CHCH_2CH=CH(CH_2)_4CH_3} \\ | \\ \mathrm{CH_2-O-\underset{\underset{O^-}{|}}{\overset{\overset{O}{\|}}{P}}-O-CH_2CH_2-\overset{+}{N}(CH_3)_3} \end{array}$$

Solution

Following the example at the start of **Section 18.6**:


fatty acid
aminoalcohol
glycerol
phosphoric acid

✔ LEARNING CHECK 18.7 Draw a typical structure for a cephalin containing the cation of ethanolamine:

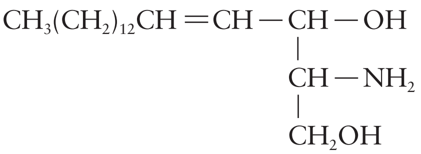
$$\text{HO—CH}_2\text{CH}_2\text{—}\overset{+}{\text{N}}\text{H}_3$$

18.7 Sphingolipids

Learning Objective 8 Draw structural formulas and describe uses for sphingolipids.

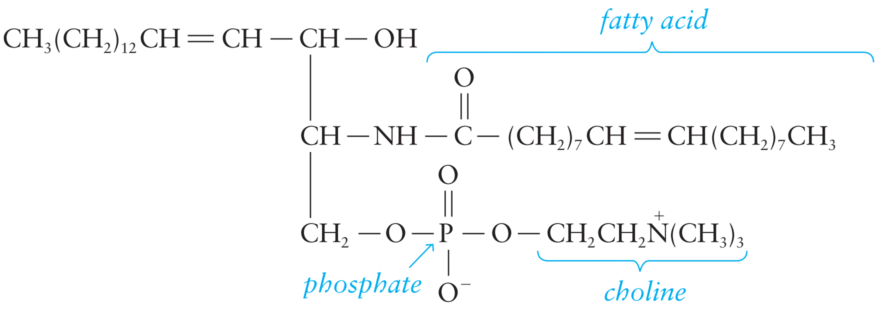
sphingolipid A complex lipid containing the aminoalcohol sphingosine.

Sphingolipids, a second type of complex lipid found in cell membranes, do not contain glycerol. Instead, they contain sphingosine, a long-chain unsaturated aminoalcohol. This substance and a typical sphingolipid, called a sphingomyelin, are represented below:

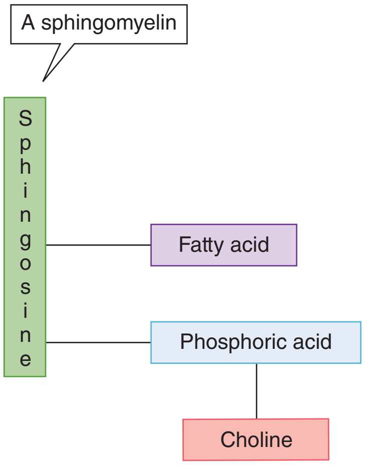


$$\begin{array}{l} CH_3(CH_2)_{12}CH{=}CH{-}CH{-}OH \\ \qquad\qquad\qquad\qquad\quad | \\ \qquad\qquad\qquad\qquad\quad CH{-}NH_2 \\ \qquad\qquad\qquad\qquad\quad | \\ \qquad\qquad\qquad\qquad\quad CH_2OH \end{array}$$

sphingosine


fatty acid
phosphate
choline

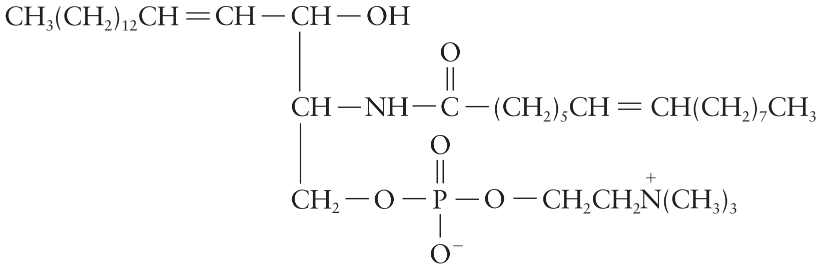
sphingomyelin


A sphingomyelin
Sphingosine
Fatty acid
Phosphoric acid
Choline

In sphingomyelin, choline is attached to sphingosine through a phosphate group. A single fatty acid is also attached to the sphingosine, but an amide linkage is involved instead of an ester linkage. A number of sphingomyelins are known; they differ only in the fatty acid component. Large amounts of sphingomyelins are found in brain and nerve tissue and in the protective myelin sheath that surrounds nerves.

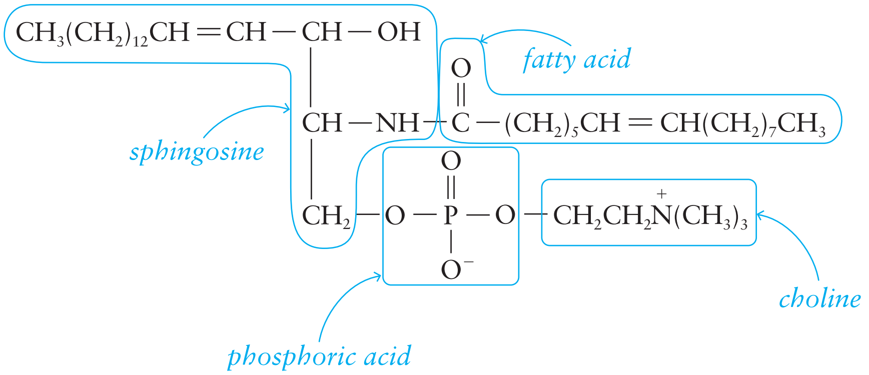
Example 18.8 Writing Sphingomyelin Structures

In the following sphingomyelin structure, circle the component parts and label each circle with one of these terms: sphingosine, fatty acid, phosphoric acid, or choline.



Solution

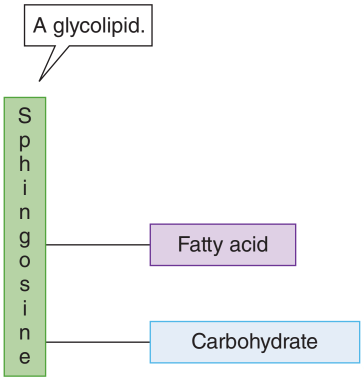
Using the structural guide above:



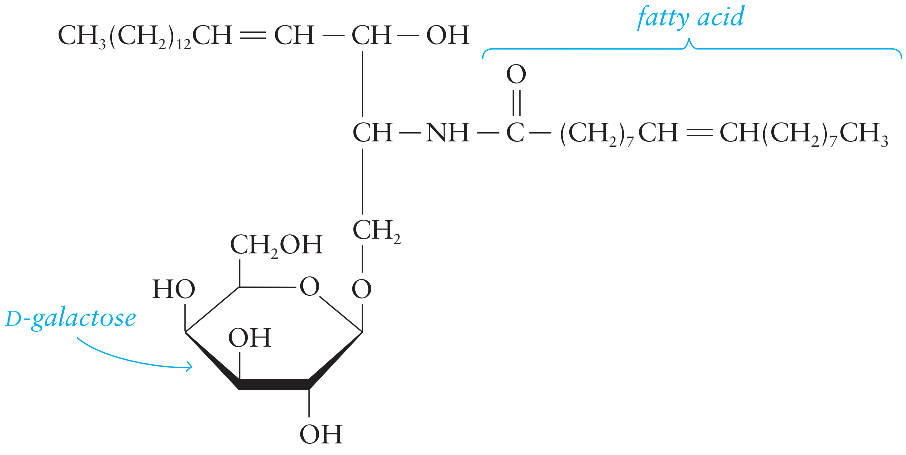
✔ **LEARNING CHECK 18.8** Write the structure of a sphingomyelin containing the fatty acid linoleic acid (shown below).

$$CH_3(CH_2)_4(CH{=}CHCH_2)_2(CH_2)_6{-}COOH$$

glycolipid A complex lipid containing a sphingosine, a fatty acid, and a carbohydrate.



Glycolipids are another type of sphingolipid. Unlike sphingomyelins, however, these complex lipids contain carbohydrates (usually monosaccharides such as glucose or galactose). Glycolipids are often called cerebrosides because of their abundance in brain tissue. The structure of a typical cerebroside is



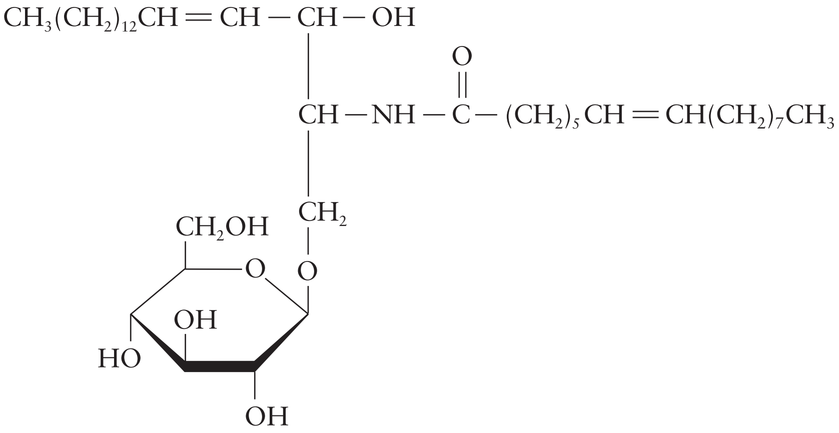
a cerebroside

Notice that, unlike the sphingomyelins, cerebrosides do not contain phosphate.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

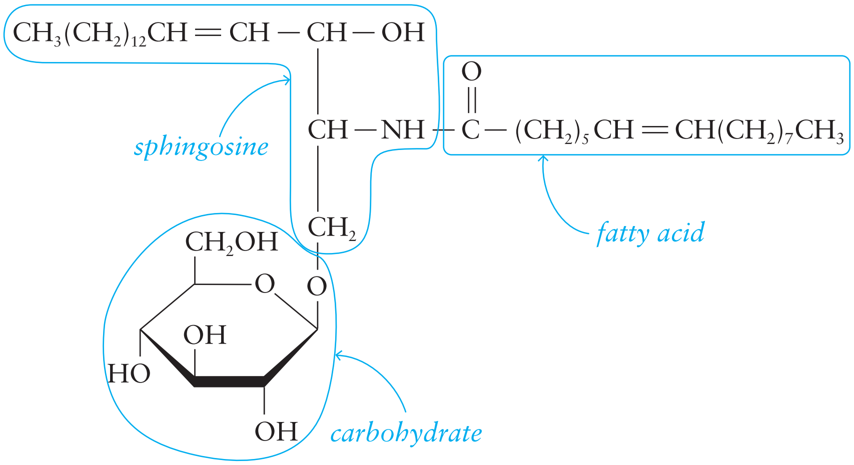
Example 18.9 Writing Glycolipid Structures

In the following glycolipid structure, circle the component parts and label each circle with one of these terms: sphingosine, fatty acid, or carbohydrate.

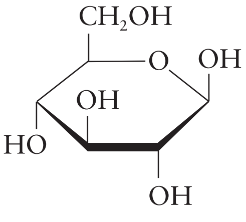


Solution

Using the marginal boxed diagram of a glycolipid as a guide:



✔ LEARNING CHECK 18.9 Write the structure of the glycolipid containing the carbohydrate glucose and the fatty acid linoleic acid.



glucose

Several human diseases are known to result from an abnormal accumulation of sphingomyelins and glycolipids in the body (see **Table 18.2**). Research has shown that each of these diseases is the result of an inherited absence of an enzyme needed to break down these complex lipids.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

TABLE 18.2 **Diseases Originating from Abnormal Metabolism and Accumulation of Glycolipids and Sphingomyelins**

Disease	Organ(s) Affected	Type of Lipid Accumulated
Tay-Sachs	Brain	Glycolipid (ganglioside G_{M2})
Gaucher's	Spleen, liver	Cerebrosides containing glucose
Niemann-Pick	Several, particularly liver and spleen	Sphingomyelins

18.8 Biological Membranes

Learning Objective 9 Describe the major features of cell membrane structure.

18.8A Cell Structure

prokaryotic cell A simple unicellular organism that contains no nucleus and no membrane-enclosed organelles.

eukaryotic cell A cell containing membrane-enclosed organelles, particularly a nucleus.

organelle A specialized structure within a cell that performs a specific function.

Two cell types are found in living organisms: prokaryotic and eukaryotic. **Prokaryotic cells**, comprising bacteria and cyanobacteria (blue-green algae), are smaller and less complex than eukaryotic cells. The more complex **eukaryotic cells** make up the tissues of all other organisms, including humans. Both types of cells are essentially tiny membrane-enclosed units of fluid containing the chemicals involved in life processes. In addition, eukaryotic cells contain small bodies called **organelles**, which are suspended in the cellular fluid, or cytoplasm. Organelles are the sites of many specialized functions in eukaryotes. The most prominent organelles and their functions are listed in **Table 18.3**. Membranes perform two vital functions in living organisms: The external cell membrane acts as a selective barrier between the living cell and its environment, and internal membranes surround some organelles, creating cellular compartments that have separate organization and functions.

TABLE 18.3 **The Functions of Some Cellular Organelles**

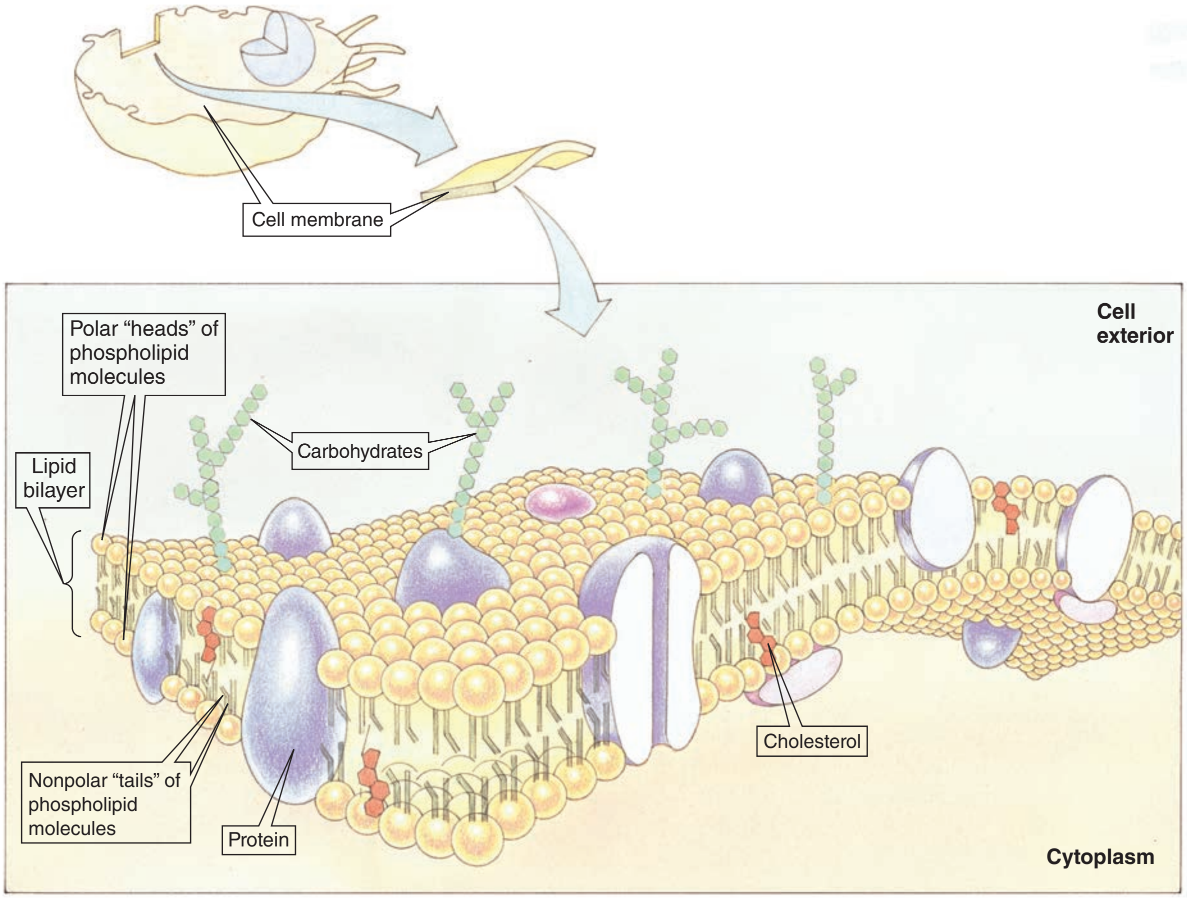
Organelle	Function
Endoplasmic reticulum	Synthesis of proteins, lipids, and other substances
Lysosome	Digestion of substances taken into cells
Microfilaments and microtubules	Cellular movements
Mitochondrion	Cellular respiration and energy production
Nucleus	Contains hereditary material (DNA), which directs protein synthesis
Plastids	Contains plant pigments such as chlorophyll (photosynthesis)
Ribosome	Protein synthesis

18.8B Membrane Structure

fluid-mosaic model A model of membrane structure in which proteins are embedded in a flexible lipid bilayer.

lipid bilayer A structure found in membranes, consisting of two sheets of lipid molecules arranged so that the hydrophobic portions are facing each other.

Most cell membranes contain about 60% lipid and 40% protein. Phosphoglycerides (such as lecithin and cephalin), sphingomyelin, and cholesterol are the predominant types of lipids found in most membranes. Precisely how the lipids and proteins are organized to form membranes has been the subject of a great deal of research. A widely accepted model called the **fluid-mosaic model** is diagrammed in **Figure 18.14**. The lipids are organized in a **lipid bilayer** in which the hydrophobic chains extend toward the inside of the bilayer, and the hydrophilic groups (the phosphate groups and other polar groups) are oriented toward the outside, where they come in contact with water (see **Figure 18.15**). Like the micelle structure discussed in **Section 18.2**, a lipid bilayer is a very stable arrangement where "like" associates with "like." The hydrophobic tails of the lipids are protected from water, and the hydrophilic heads are in a position to interact with water. When a lipid bilayer is broken and the interior hydrocarbon tails are exposed to water, the resulting repulsion causes the bilayer to re-form, and the break seals spontaneously.


Cell membrane
Cell exterior
Polar "heads" of phospholipid molecules
Lipid bilayer
Carbohydrates
Nonpolar "tails" of phospholipid molecules
Protein
Cholesterol
Cytoplasm

Elizabeth Morales-Denny. Adapted from *Understanding Human Anatomy and Physiology* by Ann Stalheim-Smith and Greg K. Fitch (Copyright © West Publishing Company, 1993). Used with permission.

FIGURE 18.14 The fluid-mosaic model of membrane structure. Phosphoglycerides are the chief lipid component. They are arranged in a bilayer. Proteins float like icebergs in a sea of lipids.

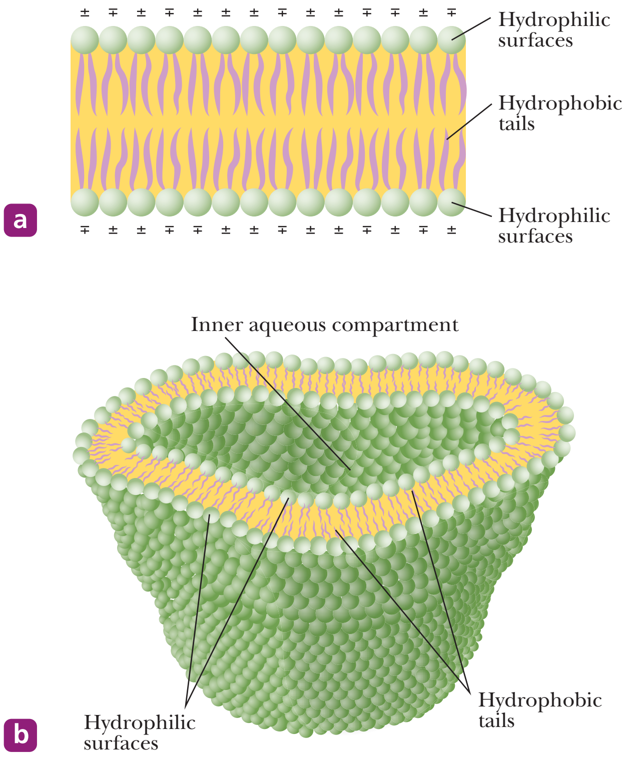

Hydrophilic surfaces
Hydrophobic tails
a
Hydrophilic surfaces
Inner aqueous compartment
Hydrophilic surfaces
Hydrophobic tails
b

FIGURE 18.15 Lipid bilayers. (a) Portion of a bilayer. Circles represent the charged polar portion of phosphoglycerides. The nonpolar hydrocarbon "tails" are within the interior of the bilayer. (b) Cutaway view of a lipid bilayer vesicle, showing an inner aqueous compartment.

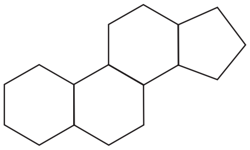
Membrane lipids usually contain unsaturated fatty acid chains that fit into bilayers more loosely than do saturated fatty acids (see **Section 18.2**). This increases the flexibility or fluidity of the membrane. Some of the proteins in the membrane float in the lipid bilayer like icebergs in the sea, whereas others extend completely through the bilayer. The lipid molecules are free to move laterally within the bilayer like dancers on a crowded dance floor—hence the term "fluid mosaic."

18.9 Steroids

Learning Objective 10 Identify the structural characteristic typical of steroids and list important groups of steroids in the body.

steroid A compound containing four rings fused in a particular pattern.

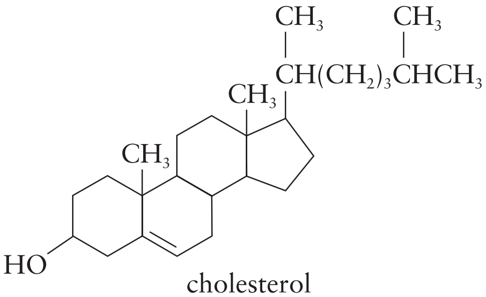
Steroids exhibit the distinguishing feature of other lipids: They are soluble in nonpolar solvents. Structurally, however, they are completely different from the lipids already discussed. **Steroids** have as their basic structure a set of three six-membered rings and a single five-membered ring fused together:



steroid ring system

18.9A Cholesterol

The most abundant steroid in the human body, and the most important, is cholesterol:



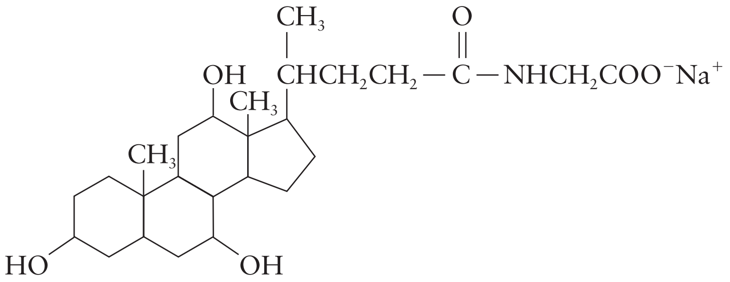
cholesterol

Cholesterol is an essential component of cell membranes and is a precursor for other important steroids, including bile salts, male and female sex hormones, vitamin D, and the adrenocorticoid hormones (see **Section 18.10**). Cholesterol for use in these important functions is synthesized in the liver. Additional amounts of cholesterol are present in the foods we eat.

On the other side of the coin, cholesterol has received much attention because of a correlation between its levels in the blood and the disease known as atherosclerosis, or hardening of the arteries (see **Section 24.1**). Although our knowledge of the role played by cholesterol in atherosclerosis is incomplete, it is now considered advisable to reduce the amount of cholesterol in the foods we eat. In addition, reducing the amount of saturated fatty acids in the diet appears to lower cholesterol production by the body.

18.9B Bile Salts

Bile is a yellowish-brown or green liver secretion that is stored and concentrated in the gallbladder. The entry of partially digested fatty food into the small intestine causes the gallbladder to contract and empty bile into the intestine. Bile does not catalyze any digestive reactions, but it is important in lipid digestion. Fats are more difficult to hydrolyze than starch and proteins because they are not soluble in water. In the watery medium of the digestive system, fats tend to form large globules with a limited surface area exposed to attack by the digestive juices. The chief constituents of bile are the bile salts and two waste components: cholesterol and bile pigments. One of the principal bile salts is sodium glycocholate:


sodium glycocholate

The bile salts act much like soaps; they emulsify the lipids and break the large globules into many smaller droplets. After such action, the total amount of lipids is still the same, but a much larger surface area is available for the hydrolysis reactions. Some researchers feel that bile salts also remove fatty coatings from particles of other types of food and thus aid in their digestion.

A second function of bile salts is to emulsify cholesterol found in the bile. Excess body cholesterol is concentrated in bile and is passed into the small intestine for excretion. If cholesterol levels become too high in the bile, or if the concentration of bile salts is too low, the cholesterol precipitates and forms gallstones (see **Figure 18.16**). The most common gallstones contain about 80% cholesterol and are colored by entrapped bile pigments.

The passage of a gallstone from the gallbladder down the common bile duct to the intestine causes excruciating pain. Sometimes one or more stones become lodged in the duct and prevent bile from passing into the duodenum, and fats can no longer be digested normally. A person afflicted with this condition feels great pain and becomes quite nauseated and ill. Bile pigments are absorbed into the blood, the skin takes on a yellow coloration, and the stool becomes gray-colored because of lack of excreted bile pigments. If the condition becomes serious, both the gallbladder and the stones can be surgically removed.

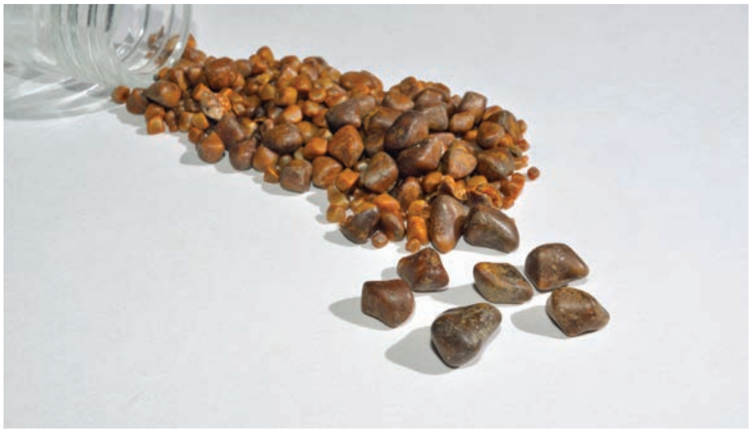
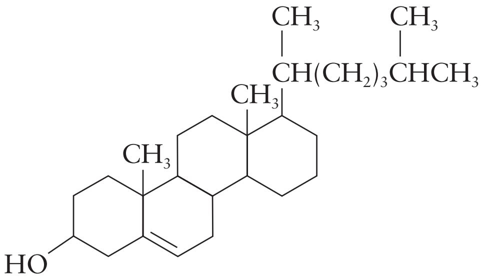

iStock.com/umdash9

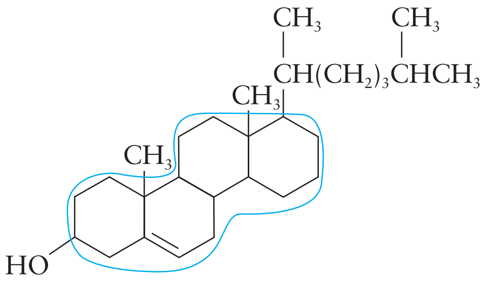
FIGURE 18.16 Gallstones form in a variety of sizes, shapes and colors.

Example 18.10 Identifying Steroids

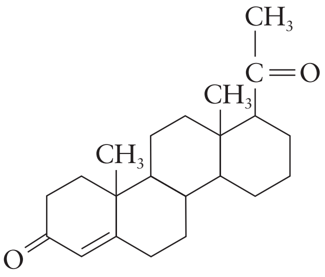
All steroids have a unique ring system. In the structure of cholesterol below, circle the ring system which makes this compound a steroid.



Solution



✔ LEARNING CHECK 18.10 In the structure of progesterone, a female sex hormone, identify with a circle the ring system that makes this compound a steroid.



18.10 Steroid Hormones

Learning Objective 11 Name the major categories of steroid hormones.

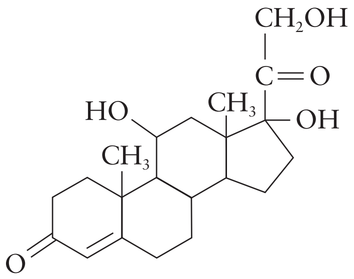
hormone A chemical messenger secreted by specific glands and carried by the blood to a target tissue, where it triggers a particular response.

A number of steroids in the body serve important roles as **hormones**. The two major categories of steroid hormones are the adrenocorticoid hormones and the sex hormones.

18.10A Adrenocorticoid Hormones

Adrenal glands are small mounds of tissue located at the top of each kidney. The outer layer of the gland, the adrenal cortex, produces a number of potent steroid hormones, the adrenocorticoids. They are classified into two groups according to function: Mineralocorticoids regulate the concentration of ions (mainly Na^+) in body fluids, and glucocorticoids enhance carbohydrate metabolism.

Cortisol, the major glucocorticoid, functions to increase the glucose and glycogen concentrations in the body. This is accomplished by the conversion of lactate and amino acids from body proteins into glucose and glycogen. The reactions take place in the liver under the influence of cortisol.



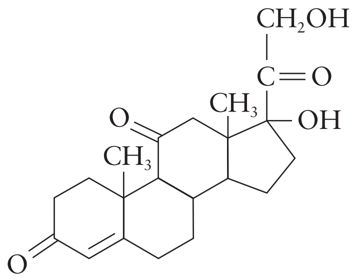
cortisol

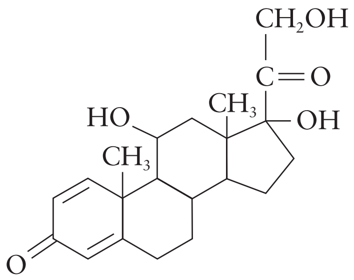
Relieves Itch Fast
2 oz Value
with Healing Aloe
MAXIMUM STRENGTH
Cortizone-10
CREME

iStock.com/NoDerog

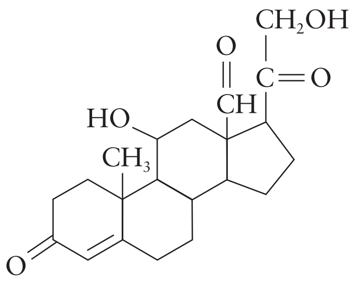
FIGURE 18.17 A valuable tool in treating inflammation, cortisone is used to treat joint swelling and pain.

Cortisol and its ketone derivative, cortisone (see **Figure 18.17**), exert powerful antiinflammatory effects in the body. These, or similar synthetic derivatives such as prednisolone, are used to treat inflammatory diseases such as rheumatoid arthritis and bronchial asthma.


cortisone


prednisolone

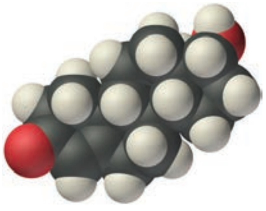
By far the most important mineralocorticoid is aldosterone, which influences the absorption of Na^+ and Cl^- in kidney tubules. An increase in the level of the hormone results in a corresponding increase in absorption of Na^+ and Cl^-. Because the concentration of Na^+ in tissues influences the retention of water, aldosterone is involved in water balance in the body.

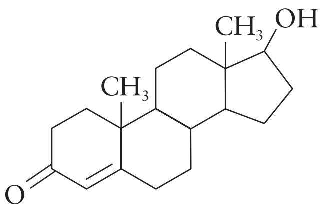

aldosterone

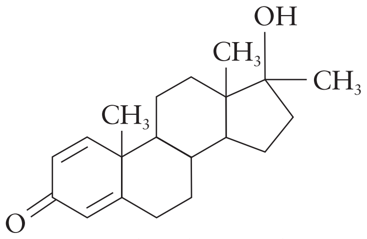
18.10B Sex Hormones

The testes and ovaries produce steroids that function as sex hormones. Secondary sex characteristics that appear at puberty—including a deep voice, beard, and increased muscular development in males and a higher voice, increased breast size, and lack of facial hair in females—develop under the influence of these sex hormones.

The testes in males perform two functions: One is to produce sperm; the other is to produce male sex hormones (androgens), the most important of which is testosterone. Testosterone promotes the normal growth of the male genital organs and aids in the development of secondary sex characteristics.


Testosterone


testosterone


methandrostenolone

Growth-promoting (anabolic) steroids, including the male hormone testosterone and its synthetic derivatives such as methandrostenolone (Dianabol), are among the most widely used drugs banned by sports-governing organizations because they are alleged to be dangerous and to confer an unfair advantage to users. These drugs, used by both male and female athletes, promote muscular development without excessive masculinization. Their use is particularly prevalent in sports where strength and muscle mass are advantageous, such as weight lifting, track-and-field events like the shot put and hammer throw, and body building.

The side effects of anabolic steroids range from acne to deadly liver tumors. Effects on the male reproductive system include testicular atrophy, a decrease in sperm count, and, occasionally, temporary infertility.

HEALTH CONNECTIONS **18.1**

Consider Olive Oil

When individuals decide to go on a weight-loss diet, they often focus primarily on the caloric content of food. When this is done, highly caloric lipids—fats and oils—are usually among the first foods to be eliminated from the diet. While this makes sense from a calorie-counting perspective, it might not when other factors are considered, such as the health benefits of some eliminated lipids.

Olive oil is a good example of a lipid that provides numerous health benefits when included in the diet (see **Health Connections 4.1**). The main type of lipid found in all types of olive oil is monounsaturated fatty acids, or MUFAs, with the 18-carbon oleic acid being the predominant component (see **Table 18.1** for its formula). MUFAs are considered to be healthy lipids. There is evidence that dietary MUFAs help lower total cholesterol levels in the body, and especially the levels of undesirable low-density lipoproteins (LDLs). Some research results show that MUFAs may help maintain normal blood clotting and normal blood pressure and may aid in the control of blood sugar levels.

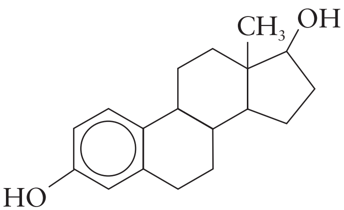
Olive oil is also known as a good source of potent antioxidants called polyphenols, which are thought to help slow the development of atherosclerosis, or narrowing of the arteries. There is even some evidence suggesting that olive oil in the diet may provide protection against age-related dementia, Alzheimer's disease, and some types of cancer, such as breast cancer.

In spite of all this good news, the high calorie content of olive oil should not be overlooked. It is important to pay attention to serving sizes and to remember to consume olive oil in place of and not in addition to other high-calorie foods. If this is not done, the beneficial health gains might be nullified by unhealthy weight gain.

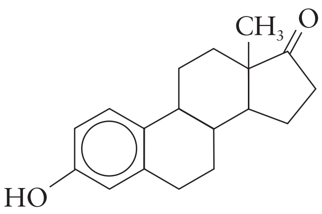
iStock.com/Valentyn Volkov

Numerous health benefits are associated with olive oil.

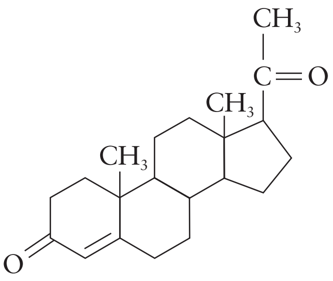
The primary female sex hormones are the estrogens: estradiol and estrone; as well as progesterone. Estrogens and progesterone are important in the reproductive process. Estrogens are involved in egg (ovum) development in the ovaries, and progesterone causes changes in the wall of the uterus to prepare it to accept a fertilized egg and maintain the resulting pregnancy.



estradiol



estrone



progesterone

18.11 Prostaglandins

Learning Objective 12 Describe the biological importance and therapeutic uses of the prostaglandins.

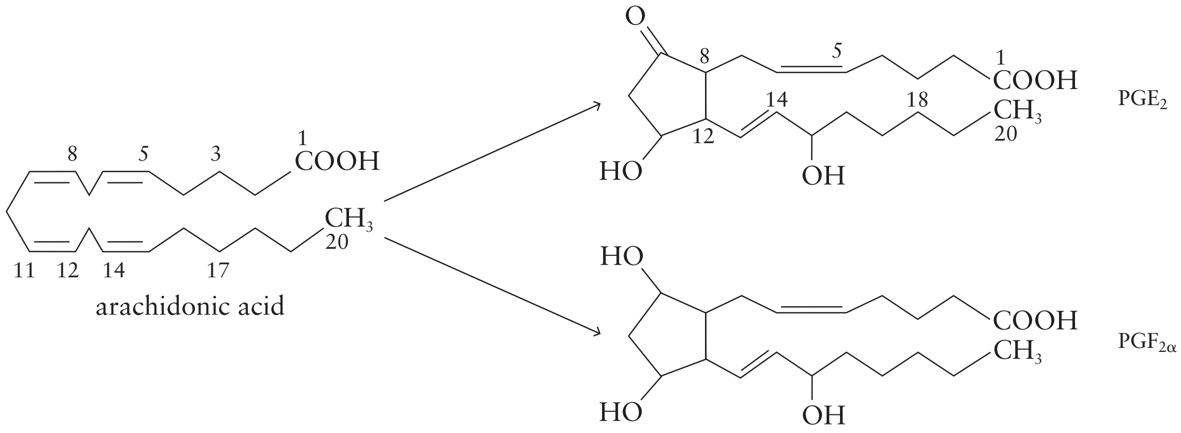
This group of compounds was given its name because the first prostaglandins were identified from the secretions of the male prostate gland. Recent research has identified as many as 20 prostaglandins in a variety of tissues within both males and females.

prostaglandin A substance derived from unsaturated fatty acids, with hormonelike effects on a number of body tissues.

Prostaglandins are cyclic compounds synthesized in the body from the 20-carbon unsaturated fatty acid arachidonic acid. Prostaglandins are designated by codes that refer to

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

the ring substituents and the number of side-chain double bonds. For example, prostaglandin E_2 (PGE_2) has a carbonyl group on the ring and a side chain containing two double bonds:



arachidonic acid

PGE_2 (18.5)

$PGF_{2\alpha}$ (18.6)

Prostaglandins are similar to hormones in the sense that they are intimately involved in a host of body processes. Clinically, it has been found that prostaglandins are involved in almost every phase of the reproductive process; they can act to regulate menstruation, prevent conception, and induce uterine contractions during childbirth. Certain prostaglandins stimulate blood clotting. They also lead to inflammation and fever. It has been found that aspirin inhibits prostaglandin production. This explains in part why aspirin is such a powerful drug in the treatment of inflammatory diseases such as arthritis.

From a medical viewpoint, prostaglandins have enormous therapeutic potential. For example, PGE_2 and PGF_2 induce labor (see **Figure 18.18**) and are used for therapeutic abortion in early pregnancy. PGE_2 in aerosol form is used to treat asthma; it opens up the bronchial tubes by relaxing the surrounding muscles. Other prostaglandins inhibit gastric secretions and are used in treating peptic ulcers. Many researchers believe that when prostaglandins are fully understood, they will be found useful for treating a much wider variety of ailments.

Reuters/Alamy Stock Photo

FIGURE 18.18 Pharmaceutical companies manufacture a number of medications containing prostaglandins.

Health Career Description

PHYSICAL THERAPY ASSISTANT

Physical therapy assistants (PTAs) work under the direction of physical therapists who hold a doctorate in physical therapy (DPT). Physical therapy assistants work with patients of all ages who experience difficulty with functional mobility due to disease, accident, or aging. PTAs teach exercises, record patient progress, take measurements, and support patient wellness through education and empathetic care. According to the American Association of Physical Therapists, "Care provided by a PTA may include teaching patients/clients exercise for mobility; strength and coordination; training for activities such as walking with crutches, canes, or walkers, massage; and the use of physical agents and electrotherapy such as ultrasound and electrical stimulation."

Physical therapy assisting is a growing career field. The Bureau of Labor Statistics predicts the demand for physical therapy assistants to grow at a rate of 26% per year and lists the average annual income for PTAs at $48, 990. This field is growing quickly because of a rapid increase in the elderly population and an increase in access to care due to the Affordable Care Act. PTAs require an associate degree from a technical college or university offering a PTA program and must pass a national licensing exam.

PTAs spend the majority of their day on their feet moving about between patients and demonstrating various exercises. They must have a minimum level of physical fitness to perform their job. Because they work closely with patients, including touching patients for treatments, they must have outstanding communication skills, and a friendly, professional demeanor, as well as the ability to protect patient confidentiality.

PTAs have the opportunity to make lasting improvements in the quality of life of patients experiencing pain and limitations in their daily lives. They work with patients of all abilities, including athletes, pregnant patients, patients preparing for or recovering from surgery, the elderly, and those experiencing unexplained pain. PTAs play an important role in helping people across a wide spectrum of circumstances to realize their full physical potential.

Sources: American Physical Therapy Association (APTA). (n.d.) Who Are Physical Therapist Assistants? Retrieved Apr. 26, 2020 from https://www.apta.org/AboutPTAs/ Bureau of Labor Statistics. (n.d.) Physical Therapist Assistants and Aides. Retrieved Apr. 26, 2020 from https://www.bls.gov/ooh/healthcare/physical-therapist-assistants-and-aides.htm

Concept Summary

18.1 Classification of Lipids

Learning Objective: Can you classify lipids as saponifiable or nonsaponifiable and list the major functions of lipids?

- Lipids are a family of naturally occurring compounds grouped together on the basis of their relative insolubility in water and solubility in nonpolar solvents.
- Lipids are energy-rich compounds that are used as waxy coatings, energy storage compounds, and as structural components by organisms.
- Lipids are classified as saponifiable (ester-containing) or nonsaponifiable.
- Saponifiable lipids are further classified as simple or complex, depending on the number of structural components.

18.2 Fatty Acids

Learning Objective: Can you describe four general characteristics of fatty acids?

- A fatty acid consists of a long nonpolar chain of carbon atoms, with a polar carboxylic acid group at one end.
- Most natural fatty acids contain an even number of carbon atoms.
- They may be saturated, unsaturated, or polyunsaturated (containing two or more double bonds).

18.3 The Structure of Fats and Oils

Learning Objective: Can you draw structural formulas of triglycerides given the formulas of the component parts? Can you describe the structural similarities and differences of fats and oils?

- Triglycerides or triacylglycerols in the form of fats and oils are the most abundant lipids.
- Fats and oils are simple lipids that are esters of glycerol and fatty acids.
- The difference between fats and oils is the melting point, which is essentially a function of the fatty acids in the compound.

18.4 Chemical Properties of Fats and Oils

Learning Objective: Can you write key reactions for fats and oils?

- Fats and oils can be hydrolyzed in the presence of acid to produce glycerol and fatty acids.
- When the hydrolysis reaction is carried out in the presence of a strong base, salts of the fatty acids (soaps) are produced.
- During hydrogenation, some multiple bonds of unsaturated fatty acids contained in fats or oils are reacted with hydrogen and converted to single bonds.

18.5 Waxes

Learning Objective: Can you compare the structures of fats and waxes?

- Waxes are simple lipids composed of a fatty acid esterified with a long-chain alcohol.
- Waxes are insoluble in water and serve as protective coatings in nature.

18.6 Phosphoglycerides

Learning Objective: Can you draw structural formulas and describe uses of phosphoglycerides?

- Phosphoglycerides consist of glycerol esterified to two fatty acids and phosphoric acid.
- The phosphoric acid is further esterified to choline (in the lecithins) and to ethanolamine or serine (in the cephalins).
- The phosphoglycerides are particularly important in membrane formation.

18.7 Sphingolipids

Learning Objective: Can you draw structural formulas and describe uses for sphingolipids?

- These complex lipids contain a backbone of sphingosine rather than glycerol and only one fatty acid component.
- They are abundant in brain and nerve tissue.

18.8 Biological Membranes

Learning Objective: Can you describe the major features of cell membrane structure?

- Membranes surround tissue cells as a selective barrier, and they encase the organelles found in eukaryotic cells.
- Membranes contain both proteins and lipids.
- According to the fluid-mosaic model, the lipids are arranged in a bilayer fashion with the hydrophobic portions on the inside of the bilayer.
- Proteins float in the bilayer.

18.9 Steroids

Learning Objective: Can you identify the structural characteristic typical of steroids and list important groups of steroids in the body?

- Steroids are compounds that have four rings fused together in a specific way.
- The most abundant steroid in humans is cholesterol.
- Cholesterol serves as a starting material for other important steroids such as bile salts, adrenocorticoid hormones, and sex hormones.

18.10 Steroid Hormones

Learning Objective: Can you name the major categories of steroid hormones?

- Hormones are chemical messengers, synthesized by specific glands, that affect various target tissues in the body.
- The adrenal cortex produces a number of steroid hormones that regulate carbohydrate utilization (the glucocorticoids) and electrolyte balance (the mineralocorticoids).
- The testes and ovaries produce steroid hormones that determine secondary sex characteristics and regulate the reproductive cycle in females.

18.11 Prostaglandins

Learning Objective: Can you describe the biological importance of therapeutic uses of the prostaglandins?

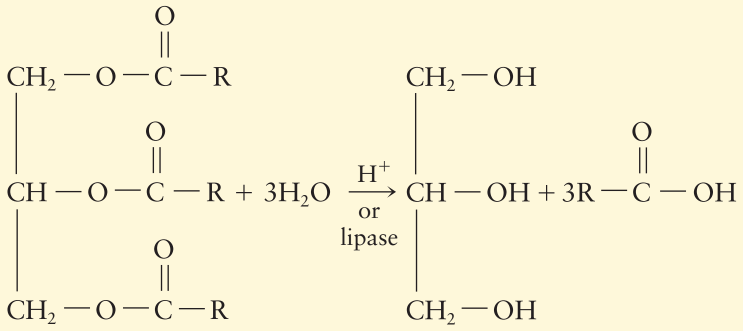
- These compounds are synthesized from the 20-carbon fatty acid arachiodonic acid.
- They exert many hormone-like effects on the body.
- They are used therapeutically to induce labor, treat asthma, and control gastric secretions.

Key Terms and Concepts

- Cephalin (18.6)
- Complex lipid (18.1)
- Essential fatty acid (18.2)
- Eukaryotic cell (18.8)
- Fat (18.3)
- Fluid-mosaic model (18.8)
- Glycolipid (18.7)
- Hormone (18.10)
- Lecithin (18.6)
- Lipid (18.1)
- Lipid bilayer (18.8)
- Micelle (18.2)
- Oil (18.3)
- Organelle (18.8)
- Phosphoglyceride (18.6)
- Phospholipid (18.6)
- Prokaryotic cell (18.8)
- Prostaglandin (18.11)
- Simple lipid (18.1)
- Soap (18.4)
- Sphingolipid (18.7)
- Steroid (18.9)
- Triglyceride or triacylglycerol (18.3)
- Wax (18.5)

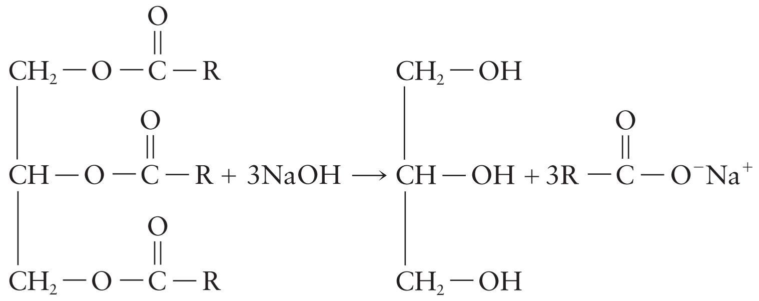
Key Equations

1. Hydrolysis of a triglyceride to glycerol and fatty acids—general reaction (**Section 18.4**):



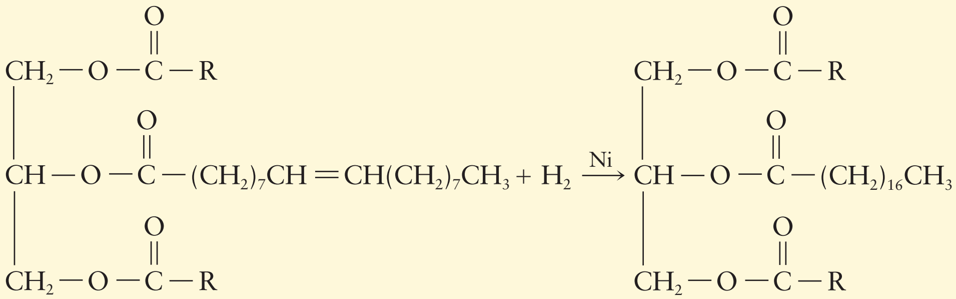
$$\begin{array}{l} CH_2-O-\overset{\overset{O}{\|}}{C}-R \\ \,| \\ CH-O-\overset{\overset{O}{\|}}{C}-R \\ \,| \\ CH_2-O-\overset{\overset{O}{\|}}{C}-R \end{array} + 3H_2O \xrightarrow[\text{lipase}]{H^+\ \text{or}} \begin{array}{l} CH_2-OH \\ \,| \\ CH-OH \\ \,| \\ CH_2-OH \end{array} + 3R-\overset{\overset{O}{\|}}{C}-OH$$

2. Saponification of a triglyceride to glycerol and fatty acid salts—general reaction (**Section 18.4**):



$$\begin{array}{l} CH_2-O-\overset{\overset{O}{\|}}{C}-R \\ \,| \\ CH-O-\overset{\overset{O}{\|}}{C}-R \\ \,| \\ CH_2-O-\overset{\overset{O}{\|}}{C}-R \end{array} + 3NaOH \longrightarrow \begin{array}{l} CH_2-OH \\ \,| \\ CH-OH \\ \,| \\ CH_2-OH \end{array} + 3R-\overset{\overset{O}{\|}}{C}-O^-Na^+$$

3. Hydrogenation of a triglyceride—general reaction (**Section 18.4**):



$$\begin{array}{l} CH_2-O-\overset{\overset{O}{\|}}{C}-R \\ \,| \\ CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_7CH=CH(CH_2)_7CH_3 \\ \,| \\ CH_2-O-\overset{\overset{O}{\|}}{C}-R \end{array} + H_2 \xrightarrow{Ni} \begin{array}{l} CH_2-O-\overset{\overset{O}{\|}}{C}-R \\ \,| \\ CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{16}CH_3 \\ \,| \\ CH_2-O-\overset{\overset{O}{\|}}{C}-R \end{array}$$

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Introduction and Classification of Lipids (Section 18.1)

18.1 What is the basis for deciding if a substance is a lipid?

18.2 List two major functions of lipids in the human body.

18.3 What functional group is common to all saponifiable lipids?

18.4 Classify the following as saponifiable or nonsaponifiable lipids:

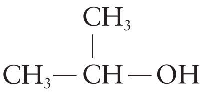
a. A steroid
b. A wax
c. A phosphoglyceride
d. A simple lipid

18.5 Classify the following as saponifiable or nonsaponifiable lipids:

a. A triglyceride
b. A complex lipid
c. A sphingolipid
d. A prostaglandin

18.6 In which of the following solvents will a lipid be soluble?

a. $CH_3(CH_2)_4CH_3$ (nonpolar)

b. 
$CH_3-\overset{\overset{\large CH_3}{|}}{CH}-OH$ (polar)

c. $CH_3CH_2-O-CH_2CH_2CH_3$ (nonpolar)

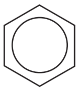
d. H_2O (polar)

18.7 In which of the following solvents will a lipid be soluble?

a. CCl_4 (nonpolar)

b. $CH_3(CH_2)_3CH_3$ (nonpolar)

c. CH_3CH_2-OH (polar)

d.  (nonpolar)

Fatty Acids (Section 18.2)

18.8 Draw the structure of a typical saturated fatty acid. Label the polar and nonpolar portions of the molecule. Which portion is hydrophobic? Hydrophilic?

18.9 Describe four structural characteristics exhibited by most fatty acids.

18.10 Describe the structure of a micelle formed by the association of fatty acid molecules in water. What forces hold the micelle together?

18.11 Name two essential fatty acids, and explain why they are called essential.

18.12 Indicate whether each of the following fatty acids is saturated or unsaturated. Which of them are solids and which are liquids at room temperature?

a. $CH_3(CH_2)_{14}COOH$

b. $CH_3(CH_2)_4CH{=}CHCH_2CH{=}CH(CH_2)_7COOH$

c. $CH_3(C_{14}H_{24})COOH$

d. $CH_3(C_{10}H_{20})COOH$

18.13 Indicate whether each of the following fatty acids is saturated or unsaturated. Which of them are solids and which are liquids at room temperature?

a. $CH_3(CH_2)_3CH{=}CHCH_2CH{=}CHCH_2COOH$

b. $CH_3(C_{12}H_{18})COOH$

c. $CH_3(C_8H_{16})COOH$

d. $CH_3(CH_2)_{11}COOH$

18.14* Explain why the melting points of unsaturated fatty acids are lower than those of saturated fatty acids.

18.15 Using **Table 18.1**, identify each of the following fatty acids as saturated, monounsaturated, or polyunsaturated. Then determine the number of carbon–carbon double bonds in each polyunsaturated fatty acid. Finally, state whether the fatty acid is an omega-3 or an omega-6 fatty acid.

a. Eicosapentaenoic acid
b. Stearic acid
c. Linoleic acid
d. Oleic acid

18.16 Using **Table 18.1**, identify each of the following fatty acids as saturated, monounsaturated, or polyunsaturated. Then determine the number of carbon-carbon double bonds in each polyunsaturated fatty acid. Finally, state whether the fatty acid is an omega-3 or an omega-6 fatty acid.

a. Arachidic acid
b. Arachidonic acid
c. Palmitoleic acid
d. Docosahexaenoic acid

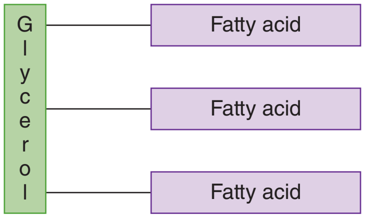
18.17 What structural feature of a fatty acid is responsible for the name omega-3 fatty acid?

The Structure of Fats and Oils (Section 18.3)

18.18 How are fats and oils structurally similar? How are they different?

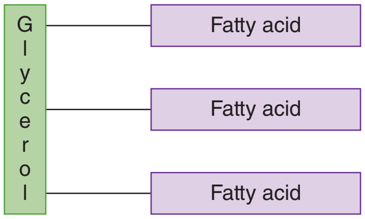
18.19 From **Figure 18.8**, arrange the following substances in order of increasing percentage of unsaturated fatty acids: chicken fat, beef fat, corn oil, butter, and sunflower oil.

18.20



Draw block diagrams similar to that above, that show the four different triglycerides that can be made from myristic acid, oleic acid, and glycerol.

18.21



Draw block diagrams similar to that above, that show the three different triglycerides that can be made from stearic acid, arachidonic acid, linolenic acid, and glycerol.

18.22 Draw the structure of a triglyceride that contains one myristic acid, one palmitoleic acid, and one linoleic acid. Identify the ester bonds.

18.23 Draw the structure of a triglyceride that contains one palmitic acid, one arachidonic acid, and one oleic acid. Identify the ester bonds. (See **Table 18.1**.)

18.24 From what general source do triglycerides tend to have more saturated fatty acids? More unsaturated fatty acids?

18.25 The percentage of fatty acid composition of two triglycerides is reported below. Predict which triglyceride has the lower melting point.

	Palmitic Acid	**Stearic Acid**	**Oleic Acid**
Triglyceride A	30.4	47.8	21.8
Triglyceride B	9.6	7.2	83.2

18.26 The percentage of fatty acid composition of two triglycerides is reported below. Predict which triglyceride has the lower melting point.

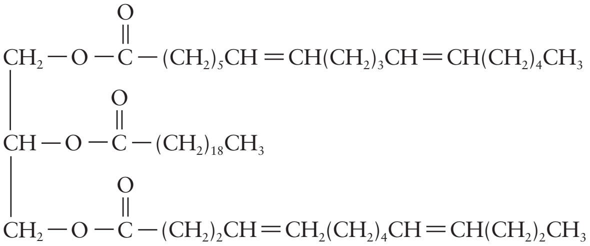
	Arachidonic Acid	**Myristic Acid**	**Palmitoleic Acid**
Triglyceride A	18.9	73.5	7.6
Triglyceride B	39.6	16.1	44.3

18.27 Why is the amount of saturated fat in the diet a health concern?

Chemical Properties of Fats and Oils (Section 18.4)

18.28 What process is used to prepare a number of useful products such as margarines and cooking shortenings from vegetable oils?

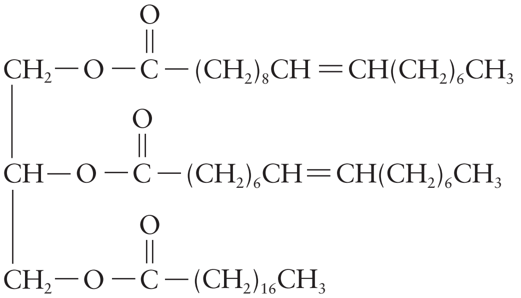
18.29



$$\begin{array}{l} CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_5CH=CH(CH_2)_3CH=CH(CH_2)_4CH_3 \\ | \\ CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{18}CH_3 \\ | \\ CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_2CH=CH_2(CH_2)_4CH=CH(CH_2)_2CH_3 \end{array}$$

Draw structural formulas for all the products you would get from the complete hydrolysis of the triglyceride above.

18.30



$$\begin{array}{l} CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_8CH=CH(CH_2)_6CH_3 \\ | \\ CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_6CH=CH(CH_2)_6CH_3 \\ | \\ CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{16}CH_3 \end{array}$$

Draw structural formulas for all the products you would get from the complete hydrolysis of the triglyceride above.

18.31 Draw structural formulas for all the products you would get from the saponification of the triglyceride in Exercise 18.29 with NaOH.

18.32 Draw structural formulas for all the products you would get from the saponification of the triglyceride in Exercise 18.30 with KOH.

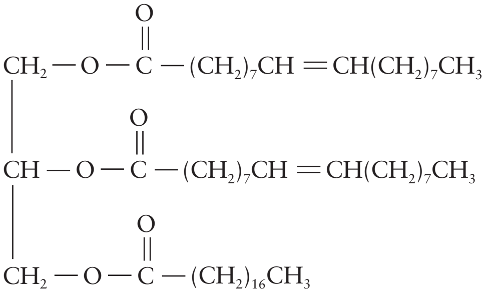
18.33 Draw a structural formula for the product you would get from the complete hydrogenation of the triglyceride in Exercise 18.29.

18.34 Draw a structural formula for the product you would get from the complete hydrogenation of the triglyceride in Exercise 18.30.

18.35 How many H_2 molecules are needed to react with the triglyceride molecule in Exercise 18.29 for its complete hydrogenation?

18.36 How many H_2 molecules are needed to react with the triglyceride molecule in Exercise 18.30 for its complete hydrogenation?

18.37 Write products for the following reactions using the oil shown below:



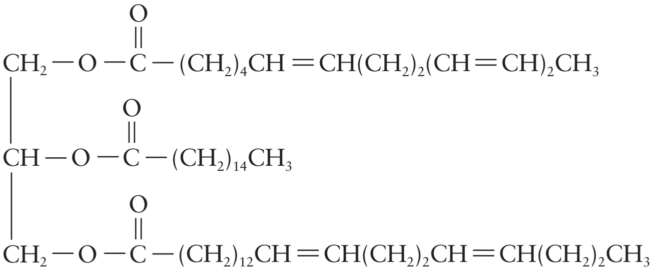
$$\begin{array}{l} CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_7CH=CH(CH_2)_7CH_3 \\ | \\ CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_7CH=CH(CH_2)_7CH_3 \\ | \\ CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{16}CH_3 \end{array}$$

a. Lipase-catalyzed hydrolysis

b. Saponification

c. Hydrogenation

18.38 Write products for the following reactions using the oil shown below:



$$\begin{array}{l} CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_4CH=CH(CH_2)_2(CH=CH)_2CH_3 \\ | \\ CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{14}CH_3 \\ | \\ CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{12}CH=CH(CH_2)_2CH=CH(CH_2)_2CH_3 \end{array}$$

a. Acid-catalyzed hydrolysis

b. Saponification

c. Hydrogenation

18.39 Why is the hydrogenation of vegetable oils of great commercial importance?

18.40 In general terms, name the products of the reactions below:

a. Acid hydrolysis of a fat

b. Acid hydrolysis of an oil

c. Saponification of a fat

d. Saponification of an oil

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

18.41* Write reactions to show how each of the following products might be prepared from a typical triglyceride present in the source given. Use **Table 18.1** as an aid.

a. Glycerol from beef fat

b. Stearic acid from beef fat

c. A margarine from corn oil

d. Soaps from lard

18.42* Write reactions to show how each of the following products might be prepared from a typical triglyceride present in the source given. Use **Table 18.1** as an aid.

a. Myristic acid from coconut oil

b. Soaps from butter fat

c. Glycerol from peanut oil

d. A butter substitute from linseed oil

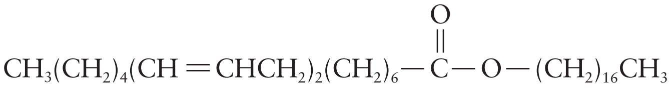
Waxes (Section 18.5)

18.43 Draw the structure of a wax formed from oleic acid and cetyl alcohol ($CH_3(CH_2)_{14}CH_2—OH$).

18.44 Like fats, waxes are esters of long-chain fatty acids. What structural difference exists between them that warrants placing waxes in a separate category?

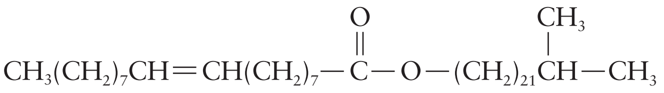
18.45 Draw the structure of a wax formed from stearic acid and 1-dodecanol ($CH_3(CH_2)_{10}CH_2—OH$)

18.46 Draw the structural formulas of the fatty acid and the long-chain alcohol used to make the following wax:



$$CH_3(CH_2)_4(CH=CHCH_2)_2(CH_2)_6-\overset{O}{\overset{\|}{C}}-O-(CH_2)_{16}CH_3$$

18.47 Draw the structural formulas of the fatty acid and the long-chain alcohol used to make the following wax:



$$CH_3(CH_2)_7CH=CH(CH_2)_7-\overset{O}{\overset{\|}{C}}-O-(CH_2)_{21}\overset{CH_3}{\overset{|}{CH}}-CH_3$$

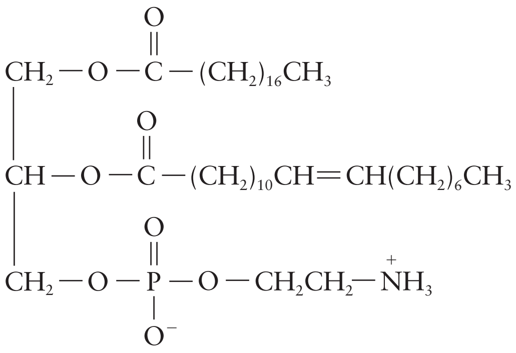
18.48 What role do waxes play in nature?

Phosphoglycerides (Section 18.6)

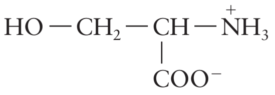
18.49 How do phosphoglycerides differ structurally from triglycerides?

18.50 Draw the general block diagram structure of a phosphoglyceride.

18.51 Circle and label the hydrophobic and hydrophilic portions of the phosphoglyceride below:



18.52 Draw the structure of a phosphoglyceride containing serine.



$$HO-CH_2-\underset{\underset{COO^-}{|}}{CH}-\overset{+}{N}H_3$$

Is it a lecithin or a cephalin?

18.53 Draw the structure of a phosphoglyceride containing choline.

$HO—CH_2CH_2—\overset{+}{N}(CH_3)_3$

18.54 Describe two biological roles served by the lecithins.

18.55 Draw the structure of a lecithin. What structural features make lecithin an important commercial emulsifying agent in certain food products?

18.56 What is the structural difference between a lecithin and a cephalin?

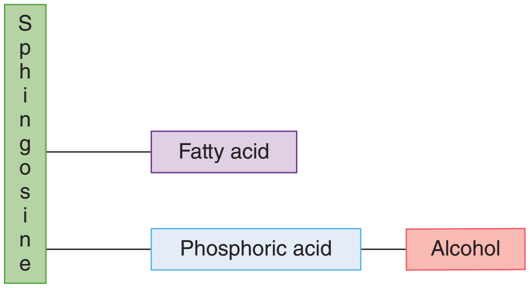
18.57 Where are cephalins found in the human body?

Sphingolipids (Section 18.7)

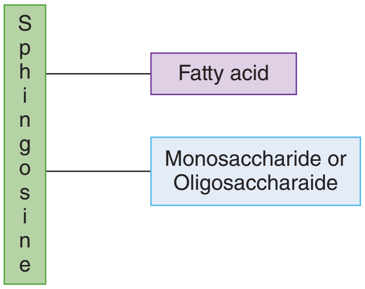
18.58 Draw the general block diagram structure of a sphingolipid.

18.59 List two structural differences between sphingolipids and phosphoglycerides.

18.60 Circle and label the hydrophobic and hydrophilic portions of the sphingolipid below.



18.61 Circle and label the hydrophobic and hydrophilic portions of the glycolipid below.



18.62 List three diseases caused by abnormal metabolism and accumulation of sphingolipids.

18.63 Describe the structural similarities and differences between the sphingomyelins and the glycolipids.

18.64 Give another name for glycolipids. In what tissues are they found?

Biological Membranes (Section 18.8)

18.65 Where would you find membranes in a prokaryotic cell? Where would you find membranes in a eukaryotic cell? What functions do the membranes serve?

18.66 What three classes of lipids are found in membranes?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

18.67 Cholesterol, a hydrophobic steroid compound, is found in cell membranes. Would you expect to find cholesterol internally or on the surfaces of the cell membrane lipid bilayer? Explain why.

18.68 How does the polarity of the phosphoglycerides contribute to their function of forming cell membranes?

18.69 Describe the major features of the fluid-mosaic model of cell membrane structure.

Steroids (Section 18.9)

18.70 Why is it suggested that some people restrict cholesterol intake in their diet?

18.71 Draw the characteristic chemical structure that applies to all steroid molecules.

18.72 Explain how bile salts aid in the digestion of lipids.

18.73 List three important groups of compounds the body synthesizes from cholesterol. Give the location in bodily tissues where cholesterol is an essential component.

18.74 Cholesterol and bile salts, such as glycocholate, are steroids. Explain how structural differences between cholesterol and glycocholate allow glycocholate to emulsify cholesterol for excretion from the gall bladder.

18.75 What symptoms might indicate the presence of gallstones in the gallbladder?

18.76 What is the major component in gallstones?

Steroid Hormones (Section 18.10)

18.77 What is a hormone? What are the two major categories of steroid hormones?

18.78 Name the two groups of adrenocorticoid hormones, give a specific example of each group, and explain the function of those compounds in the body.

18.79 How are testosterone and progesterone structurally similar? How are they different?

18.80 Name the primary male sex hormone and the three principal female sex hormones.

18.81 Compare the structures of testosterone, methandrostenolone, and progesterone. What structural feature makes the synthetic methandrostenolone a male sex hormone and not a female sex hormone?

18.82 Why do athletes use anabolic steroids? What side effects are associated with their use?

18.83 What role do the estrogens and progesterone serve in preparation for pregnancy?

Prostaglandins (Section 18.11)

18.84 What structural features characterize the prostaglandins?

18.85 What compound serves as a starting material for prostaglandin synthesis?

18.86 What body processes appear to be regulated in part by prostaglandins?

18.87 Prostaglandins perform functions similar to those of hormones. Explain why prostaglandins are not considered hormones. (*Hint:* Think of their points of origin.)

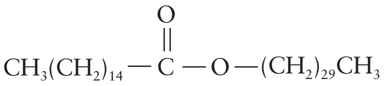
18.88 Name three therapeutic uses of prostaglandins.

Additional Exercises

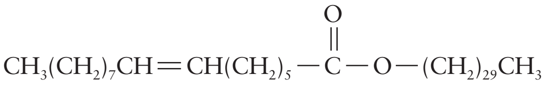
18.89 Unsaturated fatty acids are susceptible to oxidation, which causes rancidity in food products. Suggest a way to decrease the amount of oxidative rancidity occurring in a food product.

18.90 A red-brown solution of bromine (Br_2) was added to a lipid, and the characteristic red-brown bromine color disappeared. What can be deduced about the lipid structure from this information?

18.91 Which of the following waxes would have the lowest melting point? Explain your answer.

a. 

$$CH_3(CH_2)_{14}-\overset{\overset{\displaystyle O}{\|}}{C}-O-(CH_2)_{29}CH_3$$

b. 

$$CH_3(CH_2)_7CH{=}CH(CH_2)_5-\overset{\overset{\displaystyle O}{\|}}{C}-O-(CH_2)_{29}CH_3$$

18.92 Suggest a reason why complex lipids, such as phosphoglycerides and sphingomyelin, are more predominant in cell membranes than simple lipids.

18.93 Many esters are pleasantly fragrant. Examples include esters that are partially responsible for the smell of oranges and strawberries. What is the main difference between a fragrant ester and a wax? Explain why some esters are fragrant and waxes are not especially aromatic.

Chemistry for Thought

18.94 Gasoline is soluble in nonpolar solvents. Why is gasoline not classified as a lipid?

18.95 The structure of cellular membranes is such that ruptures are closed naturally. Describe the molecular forces that cause the closing to occur.

18.96 In **Figure 18.8**, the five vegetable oils listed are derived from seeds. Why do you think seeds are rich in oils?

18.97 Answer the question asked in **Figure 18.11**. How do oils used in automobiles differ chemically from vegetable oils?

18.98 Why doesn't honey dissolve beeswax?

18.99 In **Figure 18.5** (where the nonpolar tails are together), why is the structure more stable than a structure in which the polar heads are together?

18.100 Why are there so many structurally different kinds of lipids?

18.101 In what ways are the structural features of lecithin similar to those of a soap?

18.102 When a doughnut is placed on a napkin, the napkin will often absorb a liquid and appear "moist." What is most likely the nature of the liquid?

19 Proteins

hedgehog94/Shutterstock.com

Health Career Focus

OPTICIAN

"These contacts are comfortable, but avoid the temptation to sleep in them. And it's important to use this solution that removes protein buildup," I explain to my client. "Your eye adds a little protein every day. At first, it helps the lens feel comfortable, but over time, it can cause problems. You want to rub the lens in your hand—the friction helps loosen the protein and an enzyme in the solution dissolves it."

I feel that explaining "how things work" helps my clients comply with instructions. If you just give someone the "rules," with no reason why, they're likely to do their own thing—like sleep in their contacts.

I enjoy teaching people about vision and helping them pick out eyeglass frames. I also like the scientific and technical side of my job that incorporates math and chemistry. I enjoy helping people with one of the most important aspects of their health—eyesight.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Identify the characteristic parts of alpha-amino acids. **(Section 19.1)**
2. Draw structural formulas to illustrate the various ionic forms assumed by amino acids. **(Section 19.2)**
3. Write reactions to represent the formation of peptides and proteins. **(Section 19.3)**
4. Describe uses for important peptides. **(Section 19.4)**
5. Describe proteins in terms of the following characteristics: size, function, classification as fibrous or globular, and classification as simple or conjugated. **(Section 19.5)**
6. Explain what is meant by the primary structure of proteins. **(Section 19.6)**
7. Describe the role of hydrogen bonding in the secondary structure of proteins. **(Section 19.7)**
8. Describe the role of side-chain interactions in the tertiary structure of proteins. **(Section 19.8)**
9. Explain what is meant by the quaternary structure of proteins. **(Section 19.9)**
10. Describe the conditions that can cause proteins to hydrolyze or become denatured. **(Section 19.10)**

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

THE NAME *protein*, coined more than 100 years ago, is derived from the Greek *proteios*, which means "of first importance," and is appropriate for these most important of all biological compounds. Proteins are indispensable components of all living things, where they play crucial roles in all biological processes. In this chapter, we begin with a discussion of the structures and chemistry of the common amino acids, then progress to show how combinations of amino acids form large molecules called peptides and larger molecules called proteins.

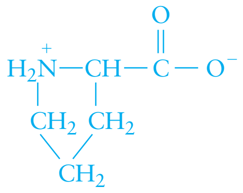
19.1 The Amino Acids

Learning Objective 1 Identify the characteristic parts of alpha-amino acids.

19.1A Structure

All proteins, regardless of their origin or biological function, are structurally similar. They are polymers consisting of chains of amino acids chemically bound to each other. As the name implies, an amino acid is an organic compound that contains both an amino group and a carboxylate group in ionic form (see **Section 19.2**). Hundreds of different amino acids, both synthetic and naturally occurring, are known, but only 20 are commonly found in natural proteins. The amino acids in proteins are called **alpha (α)-amino acids** because the amino group is attached to the α carbon (the carbon next to the carboxylate group), as shown in **Figure 19.1**. Each amino acid has a characteristic side chain, or R group, that imparts chemical individuality to the molecule. These R side chains contain different structural features, such as aromatic rings, —OH groups, $—NH_3^+$ groups, and $—COO^-$ groups. This variety in side chains causes differences in the properties of the individual amino acids and the proteins containing different combinations of them.

alpha-amino acid An organic compound containing both an amino group and a carboxylate group, with the amino group attached to the carbon next to the carboxylate group.



The structure of proline differs slightly from the general formula because the amino group and R group are part of a ring.

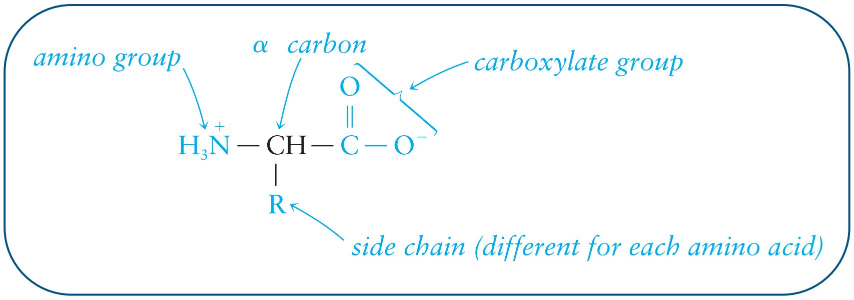
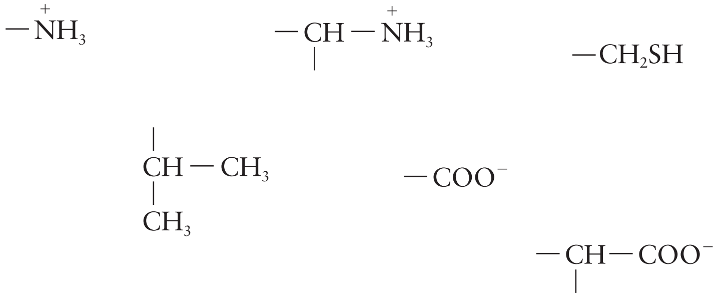

amino group
α carbon
carboxylate group
$H_3\overset{+}{N}—CH—\overset{O}{\overset{\|}{C}}—O^-$
R
side chain (different for each amino acid)

FIGURE 19.1 The general structure of α-amino acids shown in ionic form.

Example 19.1 Identifying α-Amino Acids

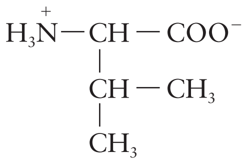
Assemble the following groups of atoms into structures for two α-amino acids:



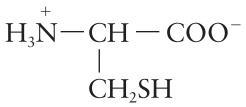
$—\overset{+}{N}H_3$ $\quad$ $—\underset{|}{CH}—\overset{+}{N}H_3$ $\quad$ $—CH_2SH$

$\overset{|}{CH}(—CH_3)—\underset{}{}$ with CH_3 below $\quad$ $—COO^-$ $\quad$ $—\underset{|}{CH}—COO^-$

Solution



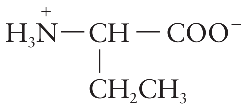
$$H_3\overset{+}{N}-\underset{\substack{|\\ CH-CH_3\\ |\\ CH_3}}{CH}-COO^-$$



$$H_3\overset{+}{N}-\underset{\substack{|\\ CH_2SH}}{CH}-COO^-$$

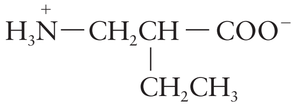
✔ LEARNING CHECK 19.1 Which of the following amino acids is an α-amino acid? (Indicate all that apply.)

a.



$$H_3\overset{+}{N}-\underset{\substack{|\\ CH_2CH_3}}{CH}-COO^-$$

b.

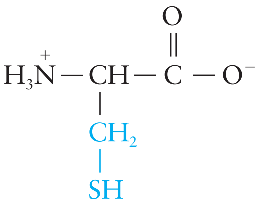


$$H_3\overset{+}{N}-CH_2\underset{\substack{|\\ CH_2CH_3}}{CH}-COO^-$$

c. $CH_3CH_2-\overset{+}{N}H_2-COO^-$

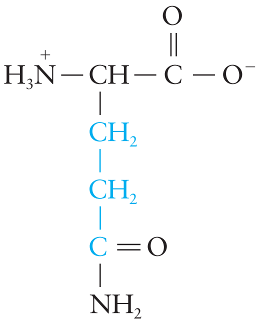
d. $CH_3-\overset{+}{N}H_2-CH_2COO^-$

The polarity of the R groups is an important characteristic and is the basis for classifying amino acids into the four groups shown in **Table 19.1**: neutral and nonpolar side chains, neutral but polar side chains, basic side chains, and acidic side chains. Note that acidic side chains contain a carboxylate group and that basic side chains contain an additional amino group. The three-letter and one-letter abbreviations that are used to represent amino acids are given after the names:



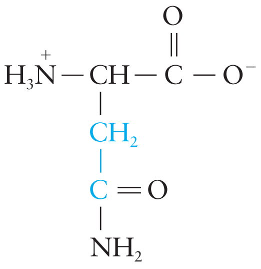
$$H_3\overset{+}{N}-\underset{\substack{|\\ CH_2\\ |\\ SH}}{CH}-\overset{\substack{O\\ \|}}{C}-O^-$$

cysteine (Cys) C



$$H_3\overset{+}{N}-\underset{\substack{|\\ CH_2\\ |\\ CH_2\\ |\\ C=O\\ |\\ NH_2}}{CH}-\overset{\substack{O\\ \|}}{C}-O^-$$

glutamine (Gln) Q



$$H_3\overset{+}{N}-\underset{\substack{|\\ CH_2\\ |\\ C=O\\ |\\ NH_2}}{CH}-\overset{\substack{O\\ \|}}{C}-O^-$$

asparagine (Asn) N

Example 19.2 Classifying Amino Acid Side Chains

For each of the following amino acids, use **Table 19.1** to identify a structural feature of the side chain that places the amino acid in that category:

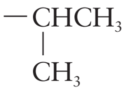
a. Threonine, neutral polar
b. Lysine, basic polar
c. Valine, neutral nonpolar
d. Aspartate, acidic polar

Solution

a. —OH

b. $-NH_3^+$

c.



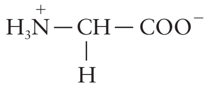
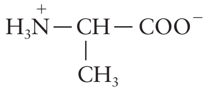
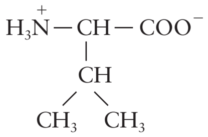
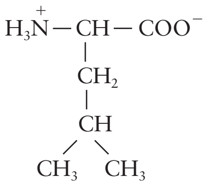
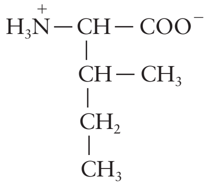
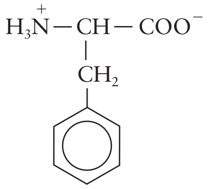
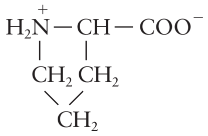
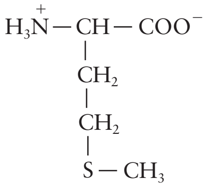
$$-\underset{\substack{|\\ CH_3}}{CH}CH_3$$

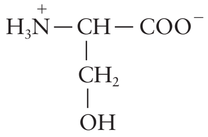
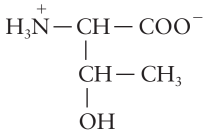
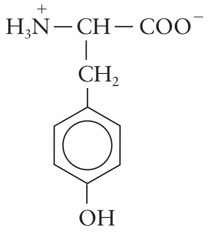
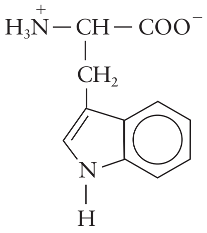
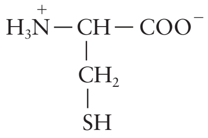
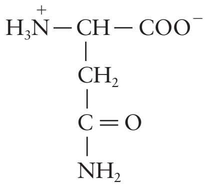
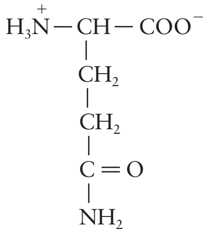
d. $-COO^-$

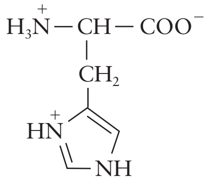
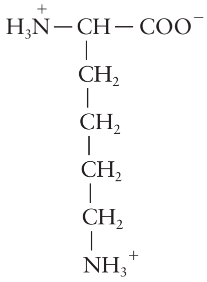
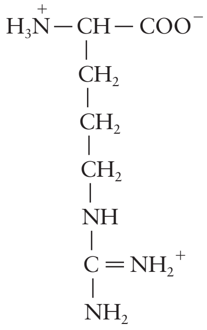
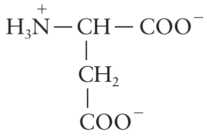
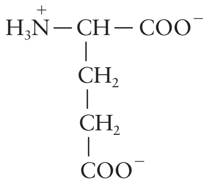
✔ LEARNING CHECK 19.2 Classify side chains that contain the following groups into one of four categories: neutral nonpolar, neutral polar, basic polar or acidic polar.

a. $-COO^-$ b. $-CH_2-S-CH_3$ c. $-NH_3^+$ d. $-CH_2-OH$

TABLE 19.1 **The Common Amino Acids of Proteins. Below Each Amino Acid Are Its Name, Its Three-Letter Abbreviation, and Its One-Letter Abbreviation**

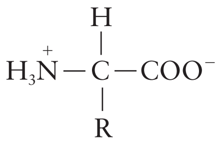
NEUTRAL, NONPOLAR SIDE CHAINS			
 Glycine (Gly) G	 Alanine (Ala) A	 Valine (Val) V	 Leucine (Leu) L
 Isoleucine (Ile) I	 Phenylalanine (Phe) F	 Proline (Pro) P	 Methionine (Met) M

NEUTRAL, POLAR SIDE CHAINS			
 Serine (Ser) S	 Threonine (Thr) T	 Tyrosine (Tyr) Y	 Tryptophan (Trp) W
 Cysteine (Cys) C	 Asparagine (Asn) N	 Glutamine (Gln) Q	

BASIC, POLAR SIDE CHAINS			ACIDIC, POLAR SIDE CHAINS	
 Histidine (His) H	 Lysine (Lys) K	 Arginine (Arg) R	 Aspartate (Asp) D	 Glutamate (Glu) E

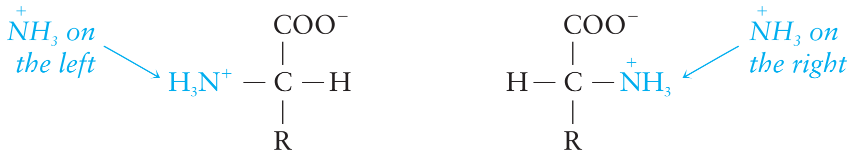
19.1B Stereochemistry

A glance at the general formula for the 20 amino acids



$$H_3\overset{+}{N}-\underset{\underset{R}{|}}{\overset{\overset{H}{|}}{C}}-COO^-$$

shows that with the exception of glycine, in which the R group is —H, there are four different groups attached to the α carbon. Thus, 19 of the 20 amino acids contain a chiral α carbon atom and can exist as two enantiomers; these are the L and D forms:



$$H_3N^+-\underset{\underset{R}{|}}{\overset{\overset{COO^-}{|}}{C}}-H \qquad H-\underset{\underset{R}{|}}{\overset{\overset{COO^-}{|}}{C}}-\overset{+}{N}H_3$$

$\overset{+}{N}H_3$ on the left

$\overset{+}{N}H_3$ on the right

an L-amino acid

a D-amino acid

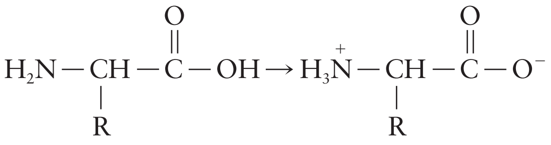
As we saw when we studied carbohydrates, one of the two possible forms usually predominates in natural systems. With few exceptions, the amino acids found in living systems exist in the L form.

19.2 Zwitterions

Learning Objective 2 Draw structural formulas to illustrate the various ionic forms assumed by amino acids.

zwitterion A dipolar ion that carries both a positive and a negative charge as a result of an internal acid–base reaction in an amino acid molecule.

The structural formulas used to this point have shown amino acids in an ionized form. The fact that amino acids are white crystalline solids with relatively high melting points and high water solubilities suggests that they exist in an ionic form. Studies of amino acids confirm that this is true both in the solid state and in solution. The presence of a carboxyl group and a basic amino group in the same molecule makes possible the transfer of a hydrogen ion in a kind of internal acid–base reaction (Reaction 19.1). The product of this reaction is a dipolar ion called a **zwitterion**.

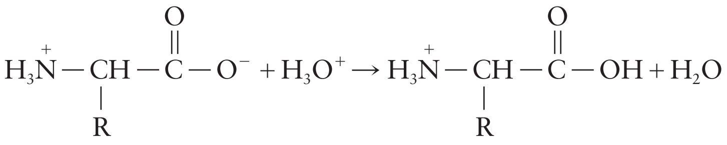


$$H_2N-\underset{\underset{R}{|}}{CH}-\overset{\overset{O}{\|}}{C}-OH \rightarrow H_3\overset{+}{N}-\underset{\underset{R}{|}}{CH}-\overset{\overset{O}{\|}}{C}-O^- \qquad (19.1)$$

nonionized form
(does not exist)

zwitterion
(present in solids
and solutions)

The structure of an amino acid in solution varies with the pH of the solution. For example, if the pH of a solution is lowered by adding a source of H_3O^+, such as hydrochloric acid, the carboxylate group ($—COO^-$) of the zwitterion can pick up a proton to form —COOH (Reaction 19.2):



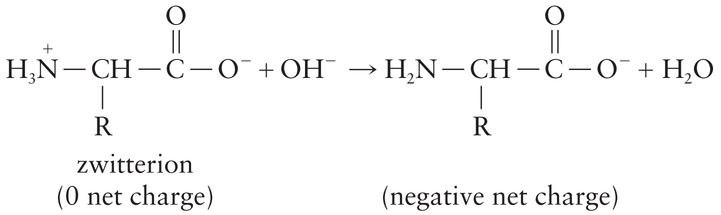
$$H_3\overset{+}{N}-\underset{\underset{R}{|}}{CH}-\overset{\overset{O}{\|}}{C}-O^- + H_3O^+ \rightarrow H_3\overset{+}{N}-\underset{\underset{R}{|}}{CH}-\overset{\overset{O}{\|}}{C}-OH + H_2O \qquad (19.2)$$

zwitterion
(0 net charge)

(positive net charge)

The zwitterion form has a net charge of 0, but the form in acid solution has a net positive charge.

When the pH of the solution is increased by adding OH^-, the $—NH_3^+$ of the zwitterion can lose a proton, and the zwitterion is converted into a negatively charged form (Reaction 19.3):



$$\overset{+}{\mathrm{H_3N}}-\underset{\mathrm{R}}{\underset{|}{\mathrm{CH}}}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{O^-} + \mathrm{OH^-} \rightarrow \mathrm{H_2N}-\underset{\mathrm{R}}{\underset{|}{\mathrm{CH}}}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{O^-} + \mathrm{H_2O} \qquad (19.3)$$

Changes in pH also affect acidic and basic side chains and those proteins in which they occur. Thus, all amino acids exist in solution in ionic forms, but the actual form (and charge) is determined by the solution pH.

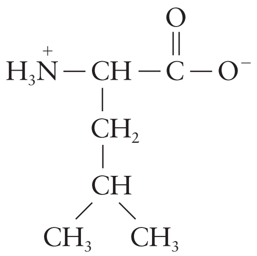
Because amino acids assume a positively charged form in acidic solutions and a negatively charged form in basic solutions, it seems reasonable to assume that at some pH between the acidic and basic extremes the amino acid will have no net charge (it will be a zwitterion). This assumption is correct, and the pH at which the zwitterion forms is called the **isoelectric point**. Each amino acid has a unique and characteristic isoelectric point; those with neutral R groups are all near a pH of 6 (that of glycine, e.g., is at pH 6.06), those with basic R groups have higher values (that of lysine is at pH 9.47), and the two acidic amino acids have lower values (that of aspartate is at pH 2.98). Proteins, which are composed of amino acids, also have characteristic isoelectric points.

isoelectric point The characteristic solution pH at which an amino acid has a net charge of 0.

The ability of amino acids and some proteins to react with both H_3O^+ and OH^-, as shown by Reactions 19.2 and 19.3, allows solutions of amino acids or proteins to behave as buffers. The buffering action of blood proteins is one of their most important functions.

Example 19.3 Drawing Zwitterion Structures

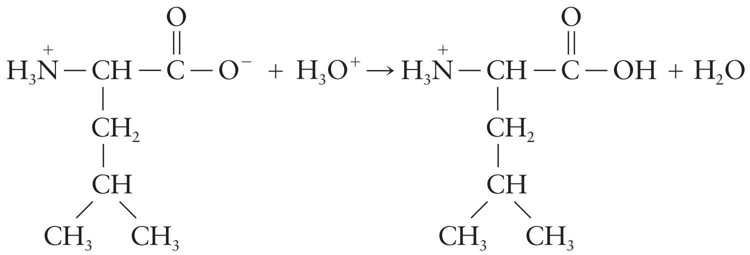
Draw the structure of the amino acid leucine



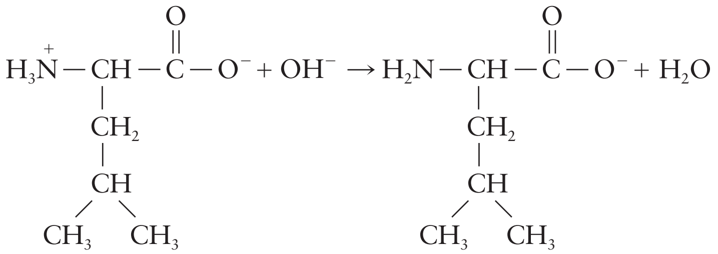
a. in acidic solution at a pH below the isoelectric point;
b. in basic solution at a pH above the isoelectric point.

Solution

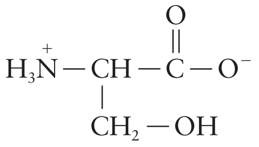
a. In acidic solution, the carboxylate group of the zwitterion picks up a proton.



b. In basic solution, the $\overset{+}{H_3N}$— group of the zwitterion loses a proton.



✔ LEARNING CHECK 19.3 Draw the structure of the amino acid serine



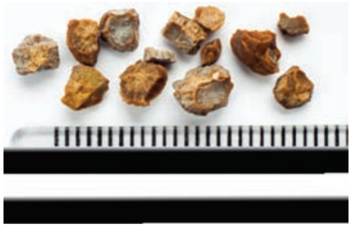
$$\overset{+}{H_3N}-\underset{\underset{CH_2-OH}{|}}{CH}-\overset{\overset{O}{\|}}{C}-O^-$$

a. in acidic solution at a pH below the isoelectric point;
b. in basic solution at a pH above the isoelectric point.

19.3 Reactions of Amino Acids

Learning Objective 3 Write reactions to represent the formation of peptides and proteins.

Amino acids can undergo reactions characteristic of any functional group in the molecule. This includes reactions of the carboxylate group, the amino group, and any other functional groups attached to the R side chain. However, two reactions are of special interest because of their influence in determining protein structure.

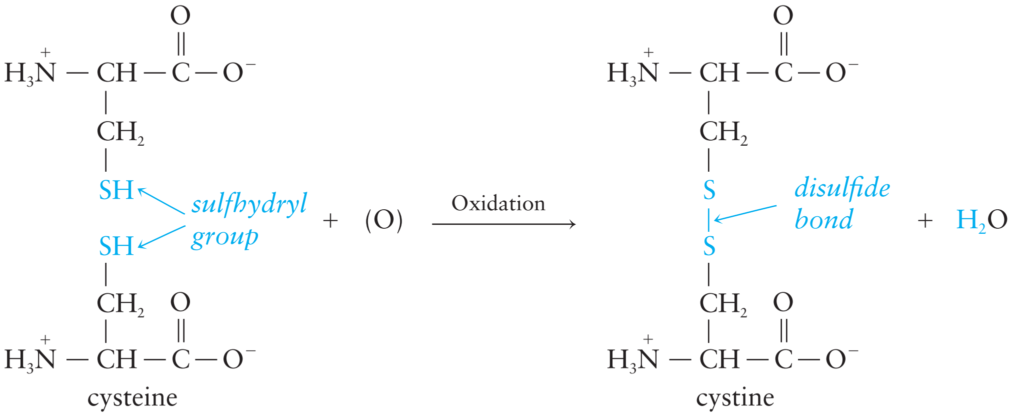


iStock.com/piotr_malczyk

FIGURE 19.2 Cystine can sometimes crystallize in the urine, leading to cystine stones (cystinuria).

19.3A Oxidation of Cysteine

Cysteine, the only sulfhydryl (—SH)-containing amino acid of the 20 commonly found in proteins, has a chemical property not shared by the other 19. We learned in **Section 13.9** that a sulfhydryl group can easily be oxidized to form a disulfide bond (—S—S—). Thus, two cysteine molecules react readily to form a disulfide compound called cystine (see **Figure 19.2**). The disulfide, in turn, is easily converted to —SH groups by the action of reducing agents:



(19.4)

As will be seen, this reaction is important in establishing the structure of some proteins.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS **19.1**

Higher-Protein Diet

There is extensive debate among experts over which type of diet is the most effective for weight loss. Protein has several potential benefits due to its effect on hunger, metabolism, and body composition. Of the three macronutrients—protein, carbohydrates, and fat—protein has the greatest ability to satisfy hunger, which is critical for dieters. Studies have found that eating larger amounts of protein, especially at breakfast, helps improve hunger control throughout the day.

Protein can also boost metabolism slightly, which is particularly important during dieting, when metabolism can drop significantly. Protein may also benefit metabolism through its impact on body composition. Research has shown that protein in the diet can help maintain lean body mass during weight loss, particularly when combined with resistance training.

Finally, eating slightly more protein during weight loss may help preserve bone mineral content, which is particularly important in women as they get older and their risk of osteoporosis increases.

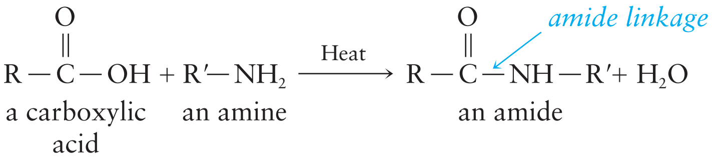
The bottom line is that calories count the most when it comes to losing weight. However, consuming a slightly higher percentage of protein (25–30%) while consuming fewer calories may make weight loss slightly easier and more sustainable.

TheFarAwayKingdom/Shutterstock.com

Protein satisfies hunger.

19.3B Peptide Formation

In **Section 16.4** we noted that amides could be thought of as being derived from a carboxylic acid and an amine (Reaction 19.5), although in actual practice the acid chlorides or acid anhydrides are generally used.

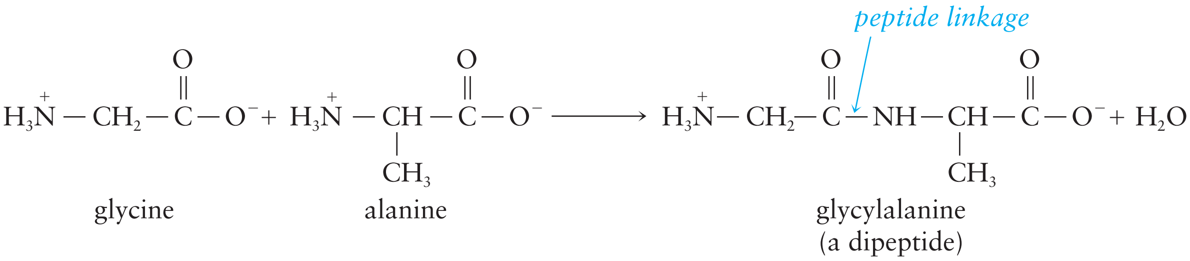


$$R-\overset{\overset{O}{\|}}{C}-OH + R'-NH_2 \xrightarrow{\text{Heat}} R-\overset{\overset{O}{\|}}{C}-NH-R' + H_2O \qquad (19.5)$$

In the same hypothetical way, it is possible to envision the carboxylate group of one amino acid reacting with the amino group of a second amino acid. For example, glycine could combine with alanine:

dipeptide A compound formed when two amino acids are bonded by an amide linkage.

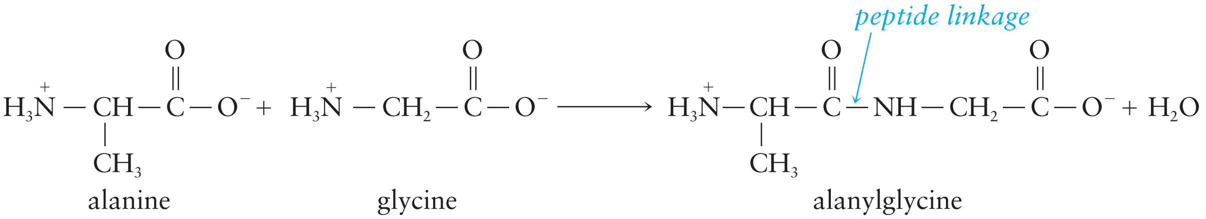
peptide linkage or peptide bond The amide linkage between amino acids that results when the amino group of one acid reacts with the carboxylate group of another.



$$H_3\overset{+}{N}-CH_2-\overset{\overset{O}{\|}}{C}-O^- + H_3\overset{+}{N}-\underset{\underset{CH_3}{|}}{CH}-\overset{\overset{O}{\|}}{C}-O^- \longrightarrow H_3\overset{+}{N}-CH_2-\overset{\overset{O}{\|}}{C}-NH-\underset{\underset{CH_3}{|}}{CH}-\overset{\overset{O}{\|}}{C}-O^- + H_2O \qquad (19.6)$$

Compounds of this type made up of two amino acids are called **dipeptides**, and the amide linkage that holds them together is called a **peptide linkage** or **peptide bond**.

It is important to realize that a different dipeptide could also form by linking glycine and alanine the other way (alanine on the left in this case):



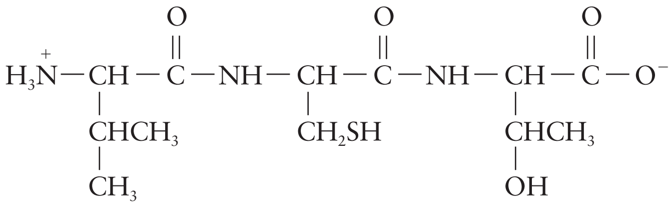
$$H_3\overset{+}{N}-\underset{\underset{CH_3}{|}}{CH}-\overset{\overset{O}{\|}}{C}-O^- + H_3\overset{+}{N}-CH_2-\overset{\overset{O}{\|}}{C}-O^- \longrightarrow H_3\overset{+}{N}-\underset{\underset{CH_3}{|}}{CH}-\overset{\overset{O}{\|}}{C}-NH-CH_2-\overset{\overset{O}{\|}}{C}-O^- + H_2O$$

(19.7)

Glycylalanine and alanylglycine are structural isomers of each other, and each has a unique set of properties. The reactions to form these and other dipeptides are more complex than Reactions 19.6 and 19.7 imply. In nature, these processes are carried out according to genetic information using a mechanism we shall examine in **Section 21.8**.

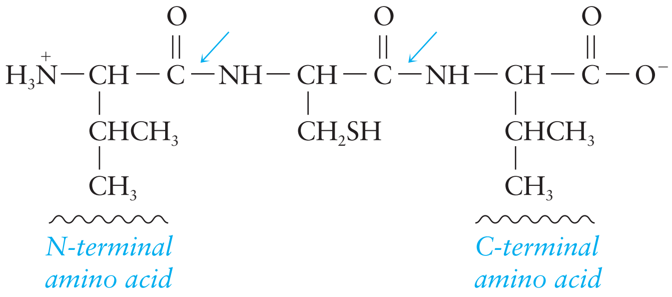
Example 19.4 Identifying Peptide Features

In the tripeptide below, identify the N-terminal and C-terminal amino acids. Use arrows to point to any peptide linkages.



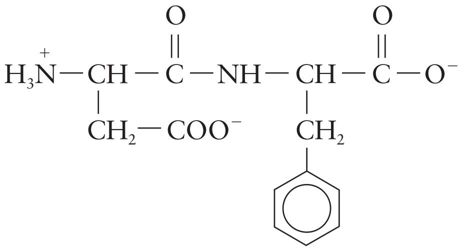
$$H_3\overset{+}{N}-\underset{\underset{\underset{CH_3}{|}}{\underset{CHCH_3}{|}}}{CH}-\overset{\overset{O}{\|}}{C}-NH-\underset{\underset{CH_2SH}{|}}{CH}-\overset{\overset{O}{\|}}{C}-NH-\underset{\underset{\underset{OH}{|}}{\underset{CHCH_3}{|}}}{CH}-\overset{\overset{O}{\|}}{C}-O^-$$

Solution

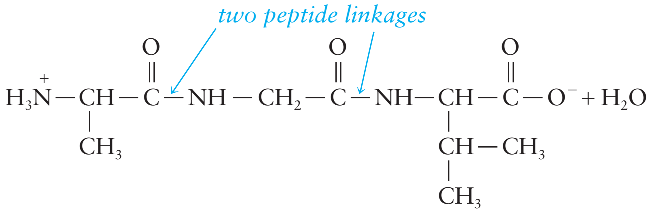


$$\underbrace{H_3\overset{+}{N}-\underset{\underset{\underset{CH_3}{|}}{\underset{CHCH_3}{|}}}{CH}}_{\text{N-terminal amino acid}}-\overset{\overset{O}{\|}}{C}\swarrow-NH-\underset{\underset{CH_2SH}{|}}{CH}-\overset{\overset{O}{\|}}{C}\swarrow-NH-\underbrace{\underset{\underset{\underset{CH_3}{|}}{\underset{CHCH_3}{|}}}{CH}-\overset{\overset{O}{\|}}{C}-O^-}_{\text{C-terminal amino acid}}$$

✔ **LEARNING CHECK 19.4** The artificial sweetener aspartame is the methyl ester of the dipeptide below. Identify the N-terminal and C-terminal amino acids. Use an arrow to indicate the peptide linkage.



The presence of amino and carboxylate groups on the ends of dipeptides allows for the attachment of a third amino acid to form a tripeptide. For example, valine could be attached to alanylglycine:



two peptide linkages

$$\overset{+}{H_3N}-\underset{\displaystyle CH_3}{\underset{|}{CH}}-\overset{\displaystyle O}{\overset{\|}{C}}-NH-CH_2-\overset{\displaystyle O}{\overset{\|}{C}}-NH-\underset{\underset{\displaystyle CH_3}{|}}{\underset{\displaystyle CH-CH_3}{\underset{|}{CH}}}-\overset{\displaystyle O}{\overset{\|}{C}}-O^- + H_2O \qquad (19.8)$$

alanylglycylvaline, a tripeptide

More amino acids can react in the same way to form a tetrapeptide, a pentapeptide, and so on, until a chain of hundreds or even thousands of amino acids has formed. The compounds with the shortest chains are often simply called **peptides**, those with longer chains are called **polypeptides**, and those with still longer chains are called **proteins**. Chemists differ about where to draw the lines in the use of these names, but generally, polypeptide chains with more than 50 amino acids are called proteins. However, the terms *protein* and *polypeptide* are often used interchangeably.

Amino acids that have been incorporated into chains are called **amino acid residues**. The amino acid residue with an unreacted or free amino group at the end of the chain is designated the **N-terminal residue**, and, according to convention, it is written on the left end of the peptide chain. Similarly, the residue with a free carboxylate group at the other end of the chain is the **C-terminal residue**; it is written on the right end of the chain. Thus, alanine is the N-terminal residue and valine is the C-terminal residue in the tripeptide alanylglycylvaline:

peptide An amino acid polymer of short chain length.

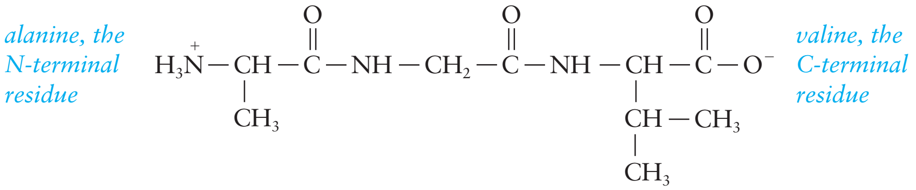
polypeptide An amino acid polymer of intermediate chain length containing up to 50 amino acid residues.

protein An amino acid polymer made up of more than 50 amino acids.

amino acid residue The parts of amino acids involved in peptide, polypeptide, or protein chain formation by the removal of water.

N-terminal residue An amino acid on the end of a chain that has an unreacted or free amino group.

C-terminal residue An amino acid on the end of a chain that has an unreacted or free carboxylate group.



alanine, the N-terminal residue

valine, the C-terminal residue

$$\overset{+}{H_3N}-\underset{\displaystyle CH_3}{\underset{|}{CH}}-\overset{\displaystyle O}{\overset{\|}{C}}-NH-CH_2-\overset{\displaystyle O}{\overset{\|}{C}}-NH-\underset{\underset{\displaystyle CH_3}{|}}{\underset{\displaystyle CH-CH_3}{\underset{|}{CH}}}-\overset{\displaystyle O}{\overset{\|}{C}}-O^-$$

Peptides are named by starting at the N-terminal end of the chain and listing the amino acid residues in order from left to right. Structural formulas and even full names for large peptides become very unwieldy and time-consuming to write. This is simplified by representing peptide and protein structures in terms of three-letter abbreviations for the amino acid residues with dashes to show peptide linkages. Thus, the structure of glycylalanine is represented by Gly-Ala. The isomeric dipeptide, alanylglycine, is Ala-Gly; in this case, alanine is the N-terminal residue, and glycine is the C-terminal residue.

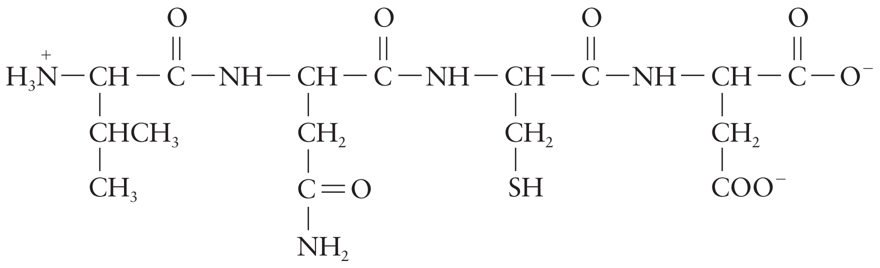
The tripeptide alanylglycylvaline can be represented by Ala-Gly-Val. In addition to this sequence, five other arrangements of these three components are possible, and each one represents an isomeric tripeptide with different properties. These sequences are Ala-Val-Gly, Val-Ala-Gly, Val-Gly-Ala, Gly-Val-Ala, and Gly-Ala-Val.

Insulin, with 51 amino acids, has 1.55×10^{66} possible sequences! From these possibilities, the body reliably produces only one, which illustrates the remarkable precision of the life process. From the simplest bacterium to the human brain cell, only the amino acid sequences needed to form essential cell peptides are produced.

Example 19.5 Drawing Peptide Structures

Draw the full structure of the tetrapeptide Val-Asn-Cys-Asp.

Solution



$$\overset{+}{H_3N}-\underset{\underset{\displaystyle CH_3}{|}}{\underset{\displaystyle CHCH_3}{\underset{|}{CH}}}-\overset{\displaystyle O}{\overset{\|}{C}}-NH-\underset{\underset{\underset{\displaystyle NH_2}{|}}{\underset{\displaystyle C=O}{|}}}{\underset{\displaystyle CH_2}{\underset{|}{CH}}}-\overset{\displaystyle O}{\overset{\|}{C}}-NH-\underset{\underset{\displaystyle SH}{|}}{\underset{\displaystyle CH_2}{\underset{|}{CH}}}-\overset{\displaystyle O}{\overset{\|}{C}}-NH-\underset{\underset{\displaystyle COO^-}{|}}{\underset{\displaystyle CH_2}{\underset{|}{CH}}}-\overset{\displaystyle O}{\overset{\|}{C}}-O^-$$

✔ **LEARNING CHECK 19.5** Use **Table 19.1** to draw the full structure of the following tetrapeptide. Label the N-terminal and C-terminal residues.

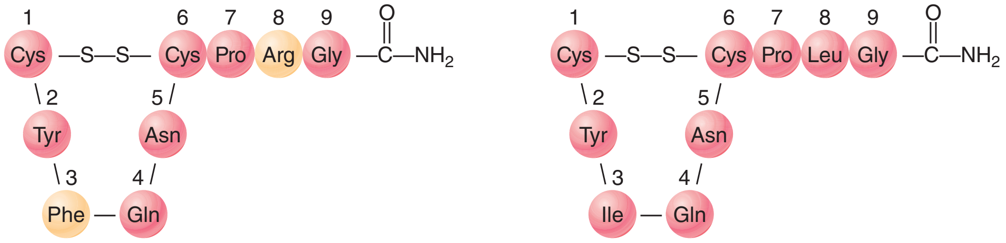
Phe-Cys-Ser-Ile

19.4 Important Peptides

Learning Objective 4 Describe uses for important peptides.

More than 200 peptides have been isolated and identified as essential to the proper functioning of the human body. The identity and sequence of amino acid residues in these peptides is extremely important to proper physiological function. Two well-known examples are vasopressin and oxytocin, which are hormones released by the pituitary gland. Each hormone is a nonapeptide (nine amino acid residues) with six of the residues held in the form of a loop by a disulfide bond (see **Figure 19.3**). The disulfide bond in these hormones is formed by the oxidation of cysteine residues in the first and sixth positions (counting from the N-terminal end) of these peptide chains. In peptides and proteins, disulfide bonds such as these that draw a single peptide chain into a loop or hold two peptide chains together are called **disulfide bridges**.

disulfide bridge A bond produced by the oxidation of —SH groups on two cysteine residues. The bond loops or holds two peptide chains together.



vasopressin **oxytocin**

FIGURE 19.3 The structures of vasopressin and oxytocin. Differences are in amino acid residues 3 and 8. The normal carboxylate groups of the C-terminal residues (Gly) have been replaced by amide groups.

iStock.com/bo1982

FIGURE 19.4 Synthetic oxytocin is sometimes given to induce labor if it has not started naturally.

Figure 19.3 shows that the structures of vasopressin and oxytocin differ only in the third and eighth amino acid residues of their peptide chains. The result of these variations is a significant difference in their biological functions. Vasopressin is known as an antidiuretic hormone (ADH) because of its action in reducing the volume of urine formed, thus conserving the body's water. It also raises blood pressure. Oxytocin causes the smooth muscles of the uterus to contract and is often administered to induce labor (see **Figure 19.4**). Oxytocin also acts on the smooth muscles of lactating mammary glands to stimulate milk ejection.

Another important peptide hormone is adrenocorticotropic hormone (ACTH). It is synthesized by the pituitary gland and consists of a single polypeptide chain of 39 amino acid residues with no disulfide bridges (see **Figure 19.5**). The major function of ACTH is to regulate the production of steroid hormones in the cortex of the adrenal gland. **Table 19.2** lists these and some other important peptide or protein hormones.

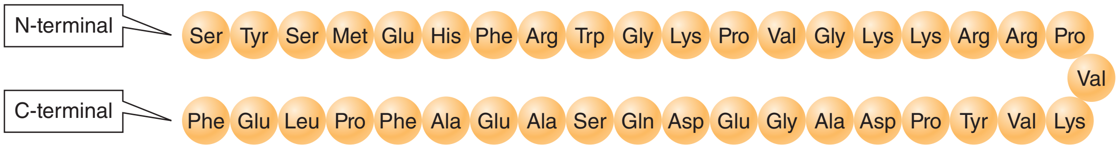

N-terminal
Ser Tyr Ser Met Glu His Phe Arg Trp Gly Lys Pro Val Gly Lys Lys Arg Arg Pro
Val
C-terminal
Phe Glu Leu Pro Phe Ala Glu Ala Ser Gln Asp Glu Gly Ala Asp Pro Tyr Val Lys

FIGURE 19.5 The amino acid sequence of ACTH.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

TABLE 19.2 Examples of Peptide or Protein Hormones

Name	Origin	Action
Adrenocorticotropic hormone (ACTH)	Pituitary	Stimulates production of adrenal hormones
Angiotensin II	Blood plasma	Causes blood vessels to constrict
Follicle-stimulating hormone (FSH)	Pituitary	Stimulates sperm production and follicle maturation
Gastrin	Stomach	Stimulates stomach to secrete acid
Glucagon	Pancreas	Stimulates glycogen metabolism in liver
Human growth hormone (HGH)	Pituitary	Stimulates growth and cell reproduction
Insulin	Pancreas	Controls metabolism of carbohydrates
Oxytocin	Pituitary	Stimulates contraction of uterus and other smooth muscles
Prolactin	Pituitary	Stimulates lactation
Somatostatin	Hypothalamus	Inhibits production of HGH
Vasopressin	Pituitary	Decreases volume of urine excreted

19.5 Characteristics of Proteins

Learning Objective 5 Describe proteins in terms of the following characteristics: size, function, classification as fibrous or globular, and classification as simple or conjugated.

19.5A Size

Proteins are extremely large natural polymers of amino acids with molecular weights that vary from about 6000 to several million units. The immense size of proteins (in the molecular sense) can be appreciated by comparing glucose with hemoglobin, a relatively small protein. Glucose has a molecular weight of 180 u, whereas the molecular weight of hemoglobin is 65,000 u (see **Table 19.3**). The molecular formula of glucose is $C_6H_{12}O_6$ and that of hemoglobin is $C_{2952}H_{4664}O_{832}N_{812}S_8Fe_4$.

Protein molecules are too large to pass through cell membranes and are contained inside the normal cells where they were formed. However, if cells become damaged by disease or trauma, the protein contents can leak out. Thus, persistent excessive amounts of proteins in the urine are indicative of damaged kidney cells. A routine urinalysis usually includes a test for protein. Similarly, a heart attack can be confirmed by the presence in the blood of certain proteins (enzymes) that are normally confined to cells in heart tissue (see **Section 20.9**).

TABLE 19.3 Molecular Weights of Some Common Proteins

Protein	Molecular Weight (u)	Number of Amino Acid Residues
Insulin	6,000	51
Cytochrome c	16,000	104
Growth hormone	49,000	191
Hemoglobin	65,000	574
Hexokinase	96,000	730
Gamma globulin	176,000	1320
Myosin	800,000	6100

19.5B Acid–Base Properties

The 20 different R groups of amino acids are important factors in determining the physical and chemical properties of proteins that contain the amino acids. Acid–base behavior is one of the most important of these properties. Proteins, like amino acids, take the form of zwitterions. The R groups of glutamate and aspartate contain —COO^- groups and provide H^+ ions, whereas the R groups of arginine and histidine are basic (see **Table 19.1**). Thus, proteins, like amino acids, have characteristic isoelectric points and can behave as buffers in solutions.

The tendency for large molecules such as proteins to remain in solution or form a stable colloidal dispersion depends to a large extent on the repulsive forces acting between molecules with like charges on their surfaces. When protein molecules are at a pH where they take forms that have a net positive or negative charge, the presence of these like charges causes the molecules to repel one another and remain dispersed. These repulsive forces are smallest at the isoelectric point, when the net molecular charges are essentially zero. Thus, protein molecules tend to clump together and precipitate from solutions in which the pH is equal to or close to the isoelectric point.

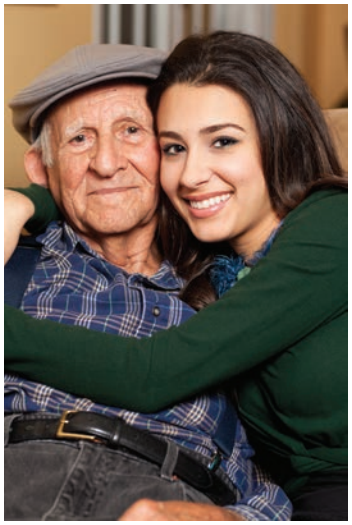

Fotoluminate LLC/Shutterstock.com

FIGURE 19.6 The elasticity of skin is due to collagen. As we age, collagen begins to break down, giving rise to wrinkles.

19.5C Protein Function

A large part of the importance of proteins results from the crucial roles they serve in all biological processes. The various functions of proteins are discussed below and summarized in **Table 19.4**.

1. **Catalytic function:** Nearly all the reactions that take place in living organisms are catalyzed by proteins functioning as enzymes. Without these catalytic proteins, biological reactions would take place too slowly to support life. Enzyme-catalyzed reactions range from relatively simple processes to the very complex, such as the duplication of hereditary material in cell nuclei. Enzymes are discussed in more detail in the next chapter.
2. **Structural function:** We saw in **Section 17.8** that the main structural material for plants is cellulose. In the animal kingdom, structural materials other than the inorganic components of the skeleton are composed of protein. Collagen, a fiberlike protein, is responsible for the mechanical strength of skin (see **Figure 19.6**) and bone. Keratin, the chief constituent of hair, skin, and fingernails, is another example.
3. **Storage function:** Some proteins provide a way to store small molecules or ions. Ovalbumin, for example, is a stored form of amino acids that is used by embryos developing in bird eggs. Casein, a milk protein, and gliadin, in wheat seeds, are also stored forms of protein intended to nourish animals and plants, respectively. Ferritin, found in all cells of the body, attaches to iron ions and forms a storage complex in humans and other animals.
4. **Protective function: Antibodies** are tremendously important proteins that protect the body from disease. These highly specific proteins combine with and help destroy viruses, bacteria, and other foreign substances that get into the blood or tissue of the body. Blood clotting, another protective process, is carried out by the proteins thrombin and fibrinogen. Without this process, even small wounds would result in life-threatening bleeding.
5. **Regulatory function:** Numerous body processes are regulated by hormones, many of which are proteins. Examples are growth hormone, which regulates the growth rate of young animals, and thyrotropin, which stimulates the activity of the thyroid gland.
6. **Nerve impulse transmission:** Some proteins behave as receptors of small molecules that pass between gaps (synapses) separating nerve cells. In this way, they transmit nerve impulses from one nerve to another. Rhodopsin, a protein found in the rod cells of the retina of the eye, functions this way in the vision process (see **Figure 19.7**).
7. **Movement function:** Every time we climb stairs, push a button, or blink an eye, we use muscles that have proteins as their major components. The proteins actin and myosin are particularly important in processes involving movement. They are long-filament proteins that slide along each other during muscle contraction.
8. **Transport function:** Numerous small molecules and ions are transported effectively through the body only after binding to proteins. For example, fatty acids are carried between fat (adipose) tissue and other tissues or organs by serum albumin, a blood protein. Hemoglobin, a well-known example, carries oxygen from the lungs to other body tissues, and transferrin is a carrier of iron in blood plasma.

antibody A substance that helps protect the body from invasion by viruses, bacteria, and other foreign substances.

iStock.com/kwasny221

FIGURE 19.7 Rhodopsin is extremely sensitive to light, and thus enables vision in low-light conditions.

TABLE 19.4 Biological Functions of Proteins

Function	Examples	Occurrence or Role
Catalysis	lactate dehydrogenase	Oxidizes lactic acid
	cytochrome c	Transfers electrons
	DNA polymerase	Replicates and repairs DNA
Structure	viral-coat proteins	Sheath around nucleic acid of viruses
	glycoproteins	Cell coats and walls
	α-keratin	Skin, hair, feathers, nails, and hooves
	β-keratin	Silk of cocoons and spiderwebs
	collagen	Fibrous connective tissue
	elastin	Elastic connective tissue
Storage	ovalbumin	Egg-white protein
	casein	A milk protein
	ferritin	Stores iron in the spleen
	gliadin	Stores amino acids in wheat
	zein	Stores amino acids in corn
Protection	antibodies	Form complexes with foreign proteins
	fibrinogen	Involved in blood clotting
	thrombin	Involved in blood clotting
Regulation	insulin	Regulates glucose metabolism
	growth hormone	Stimulates growth of bone
Nerve impulse transmission	rhodopsin	Involved in vision
	acetylcholine receptor protein	Impulse transmission in nerve cells
Movement	myosin	Thick filaments in muscle fiber
	actin	Thin filaments in muscle fiber
	dynein	Movement of cilia and flagella
Transport	hemoglobin	Transports O_2 in blood
	myoglobin	Transports O_2 in muscle cells
	serum albumin	Transports fatty acids in blood
	transferrin	Transports iron in blood
	ceruloplasmin	Transports copper in blood

Proteins perform other functions, but these are among the most important. It is easy to see that properly functioning cells of living organisms must contain many proteins. It has been estimated that a typical human cell contains 9000 different proteins, and that a human body contains about 100,000 different proteins.

Michael R. Slabaugh

FIGURE 19.8 Animal hair and spiderwebs are constructed of the fibrous proteins α-keratin and β-keratin, respectively. What properties of fibrous proteins make hair, fur, and spiderwebs useful?

19.5D Classification

Proteins can be classified by the functions just discussed. They can also be classified into two major types, fibrous and globular, on the basis of their structural shape. **Fibrous proteins** are made up of long rod-shaped or stringlike molecules that intertwine with one another and form strong fibers. They are water insoluble and are usually found as major components of connective tissue, elastic tissue, hair, and skin. Examples are collagen, elastin, and keratin (see **Figure 19.8**).

Globular proteins are more spherical and either dissolve in water or form stable suspensions in water. They are not found in structural tissue but are transport proteins, or proteins that may be moved easily through the body by the circulatory system. Examples of these are hemoglobin and transferrin.

Another classification scheme for proteins is based on composition—proteins are either simple or conjugated. **Simple proteins** are those that contain only amino acid residues. **Conjugated proteins** contain amino acid residues and other organic or inorganic components. The non–amino acid parts of conjugated proteins are called **prosthetic groups**.

fibrous protein A protein made up of long rod-shaped or stringlike molecules that intertwine to form fibers.

globular protein A spherical protein that usually forms stable suspensions in water or dissolves in water.

simple protein A protein made up entirely of amino acid residues.

conjugated protein A protein made up of amino acid residues and other organic or inorganic components.

prosthetic group The non–amino acid parts of conjugated proteins.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The type of prosthetic group present is often used to further classify conjugated proteins. For example, proteins containing lipids, carbohydrates, or metal ions are called lipoproteins, glycoproteins, and metalloproteins, respectively. Thus, the iron-containing proteins hemoglobin and myoglobin are metalloproteins. **Table 19.5** lists the common classes of conjugated proteins.

TABLE 19.5 Conjugated Proteins

Class	Prosthetic Groups	Examples
Nucleoproteins	nucleic acids (DNA, RNA)	Viruses
Lipoproteins	lipids	Fibrin in blood, serum lipoproteins
Glycoproteins	carbohydrates	Gamma globulin in blood, mucin in saliva
Phosphoproteins	phosphate groups	Casein in milk
Hemoproteins	heme	Hemoglobin, myoglobin, cytochromes
Metalloproteins	iron zinc	Ferritin, hemoglobin Alcohol dehydrogenase

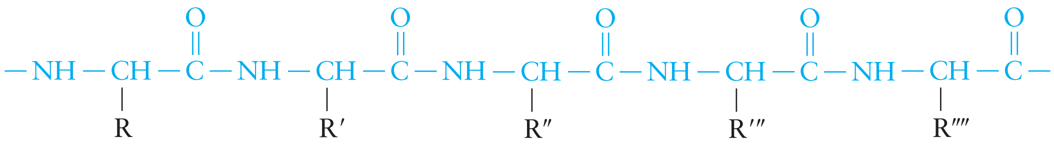
19.5E Protein Structure

As you might expect, the structures of extremely large molecules, such as proteins, are much more complex than those of simple organic compounds. Many protein molecules consist of a chain of amino acids twisted and folded into a complex three-dimensional structure. This structural complexity imparts unique features to proteins that allow them to function in the diverse ways required by biological systems. To better understand protein function, we must look at four levels of organization in their structure. These levels are referred to as primary, secondary, tertiary, and quaternary.

19.6 The Primary Structure of Proteins

Learning Objective 6 Explain what is meant by the primary structure of proteins.

Every protein, be it hemoglobin, keratin, or insulin, has a similar backbone of carbon and nitrogen atoms held together by peptide bonds:



$$-\mathrm{NH}-\underset{\underset{\displaystyle \mathrm{R}}{|}}{\mathrm{CH}}-\overset{\overset{\displaystyle \mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{NH}-\underset{\underset{\displaystyle \mathrm{R'}}{|}}{\mathrm{CH}}-\overset{\overset{\displaystyle \mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{NH}-\underset{\underset{\displaystyle \mathrm{R''}}{|}}{\mathrm{CH}}-\overset{\overset{\displaystyle \mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{NH}-\underset{\underset{\displaystyle \mathrm{R'''}}{|}}{\mathrm{CH}}-\overset{\overset{\displaystyle \mathrm{O}}{\|}}{\mathrm{C}}-\mathrm{NH}-\underset{\underset{\displaystyle \mathrm{R''''}}{|}}{\mathrm{CH}}-\overset{\overset{\displaystyle \mathrm{O}}{\|}}{\mathrm{C}}-$$

protein backbone (in color)

primary protein structure The linear sequence of amino acid residues in a protein chain.

The difference in proteins is the variation in the length of the backbone and the sequence of the side chains (R groups) that are attached to the backbone. The order in which amino acid residues are linked together in a protein is called the **primary structure**. Each different protein in a biological organism has a unique sequence of amino acid residues. It is this sequence that causes a protein chain to fold and curl into the distinctive shape that, in turn, enables the protein to function properly. As we will see in **Section 19.10**, a protein molecule that loses its characteristic three-dimensional shape cannot function.

Biochemists have devised techniques for finding the order in which the residues are linked together in protein chains. A few of the proteins whose primary structures are known are listed in **Table 19.6**.

TABLE 19.6 Some Proteins Whose Sequence of Amino Acids Is Known

Protein	Number of Amino Acid Residues
Insulin	51
Hemoglobin	
α-chain	141
β-chain	146
Myoglobin	153
Human growth hormone	191
Trypsinogen	229
Carboxypeptidase A	307
Gamma globulin	1320

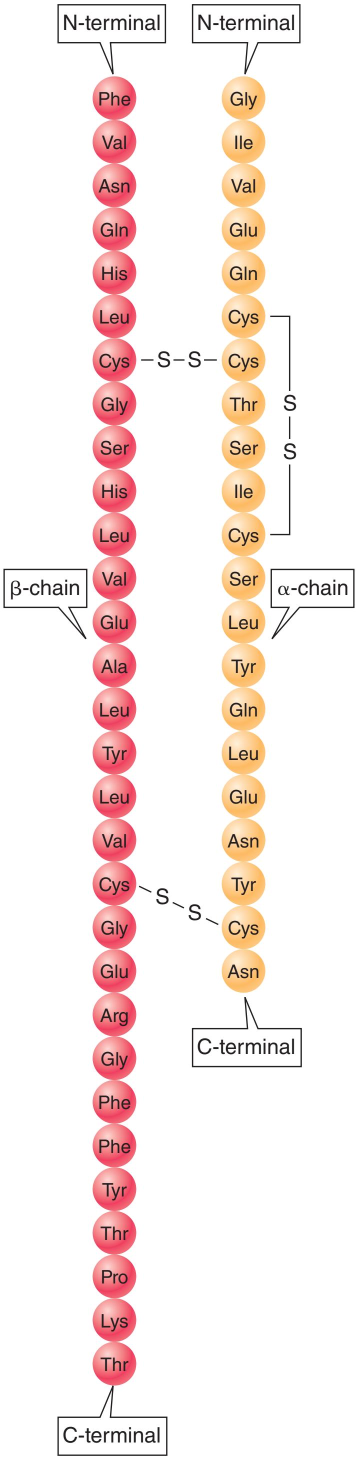


FIGURE 19.9 The amino acid sequence (primary structure) of human insulin.

Figure 19.9 shows the primary structure of human insulin. Notice that the individual molecules of this hormone consist of two chains having a total of 51 amino acid residues. In the molecule, two disulfide bridges hold the chains together, and there is one disulfide linkage within a chain. Insulin plays an essential role in regulating the use of glucose by cells. Diabetes mellitus can result when the body does not produce enough insulin or when cells do not respond to the insulin that is produced.

As we saw in the case of vasopressin and oxytocin (see **Section 19.4**), small changes in amino acid sequence can cause profound differences in the functioning of proteins. For example, a minor change in sequence in the blood protein hemoglobin causes the fatal sickle-cell disease.

Example 19.6 Writing Protein Primary Structure

Using **Figure 19.9**, write the first eight amino acids of the primary structure of the β-chain of insulin. Use three-letter abbreviations, and start at the N-terminal end.

Solution

Phe-Val-Asn-Gln-His-Leu-Cys-Gly

✔ **LEARNING CHECK 19.6** Using **Figure 19.9**, write the first eight amino acids of the primary structure of the α-chain of insulin. Use three-letter abbreviations, and start at the N-terminal end.

19.7 The Secondary Structure of Proteins

Learning Objective 7 Describe the role of hydrogen bonding in the secondary structure of proteins.

If the only structural characteristics of proteins were their amino acid sequences (primary structures), all protein molecules would consist of long chains arranged in random fashion. However, protein chains fold and become aligned in such a way that certain orderly patterns result. These orderly patterns, referred to as **secondary structures**, result from hydrogen bonding and include the α-helix (alpha-helix) and the β-pleated (beta-pleated) sheet.

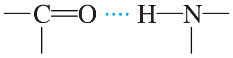
secondary protein structure The arrangement of protein chains into patterns as a result of hydrogen bonds between amide groups of amino acid residues in the chain. The common secondary structures are the α-helix and the β-pleated sheet.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

α-helix The helical structure in proteins that is maintained by hydrogen bonds.

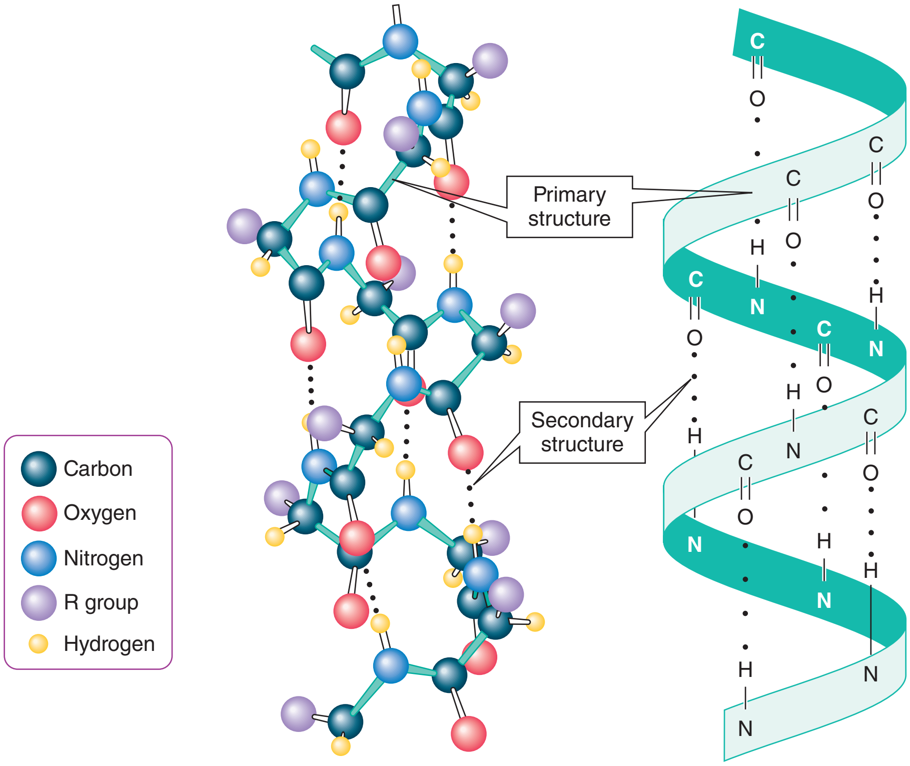
19.7A The α-Helix

In 1951, American chemists Linus Pauling and Robert Corey suggested that proteins could exist in the shape of an **α-helix**, a form in which a single protein chain twists so that it resembles a coiled helical spring (see **Figure 19.10**). The chain is held in the helical shape by numerous intramolecular hydrogen bonds between carbonyl oxygens and amide hydrogens in adjacent turns of the helical backbone:



$$-\underset{|}{C}=O \cdots H-\underset{|}{N}-$$

FIGURE 19.10 Two representations of the α-helix, showing hydrogen bonds between amide groups.

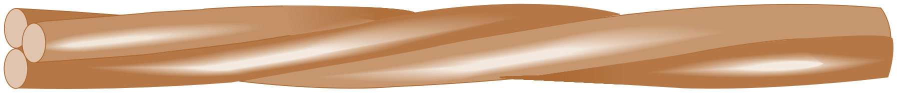


The carbonyl group of each amino acid residue is hydrogen-bonded to the amide hydrogen of the amino acid that is four residues away in the chain; thus, all amide groups in the helix are hydrogen-bonded (see **Figure 19.10**). The protein backbone forms the coil, and the side chains (R groups) extend outward from the coil.

Six years after Pauling and Corey proposed the α-helix, its presence in proteins was detected. Since that time it has been found that the amount of α-helical content is quite variable in proteins. In some it is the major structural component, whereas in others a random coil predominates and there is little or no α-helix coiling.

In the proteins α-keratin (found in hair), myosin (found in muscle), epidermin (found in skin), and fibrin (found in blood clots), two or more helices interact (supracoiling) to form a cable (see **Figure 19.11**). These cables make up bundles of fibers that lend strength to the tissue in which they are found.

FIGURE 19.11 The supracoiling of three α-helices in the keratins of hair and wool.



19.7B The β-Pleated Sheet

β-pleated sheet A secondary protein structure in which protein chains are aligned side by side in a sheetlike array held together by hydrogen bonds.

A second common type of secondary structure is found in proteins. This type, called a **β-pleated sheet**, results when several protein chains lie side by side and are held in position by hydrogen bonds between the carbonyl oxygens of one chain and the amide hydrogens of an adjacent chain (see **Figure 19.12**).

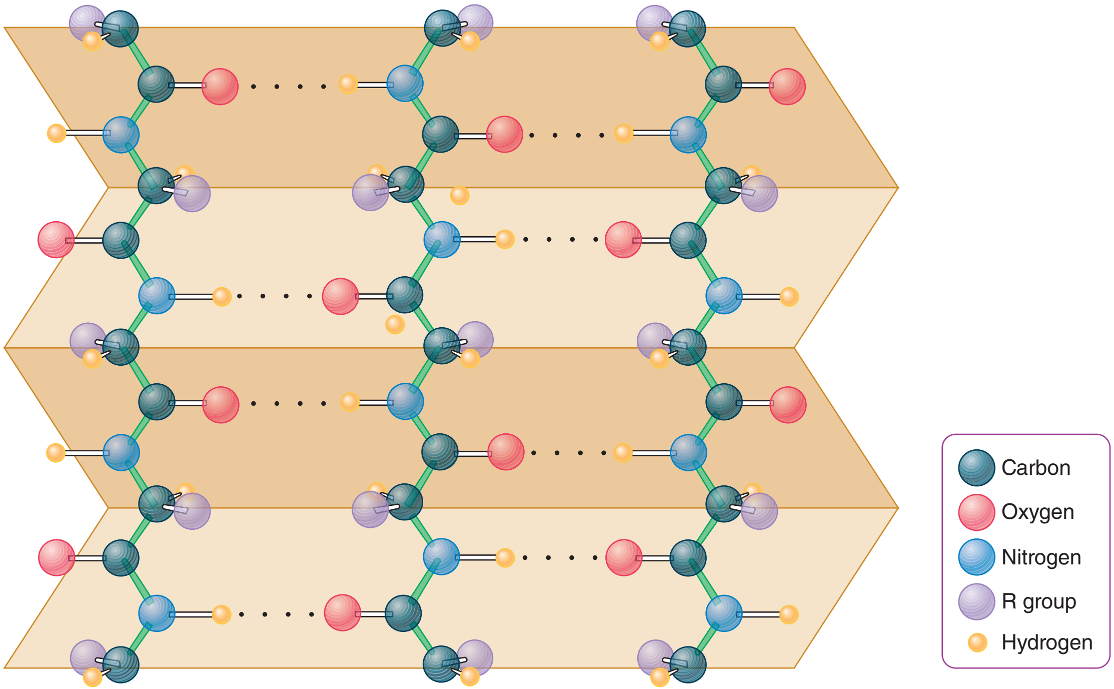


FIGURE 19.12 The β-pleated sheet. The four dots show hydrogen bonds between adjacent protein chains.

The β-pleated sheet is found extensively only in the protein of silk. However, a number of proteins in which a single polypeptide chain forms sections of a β-pleated sheet structure by folding back on itself are known. **Figure 19.13** depicts a protein chain exhibiting the β-pleated sheet, the α-helix, and other structural conformations. Note the position of the hydrogen bonds in the two secondary structures.

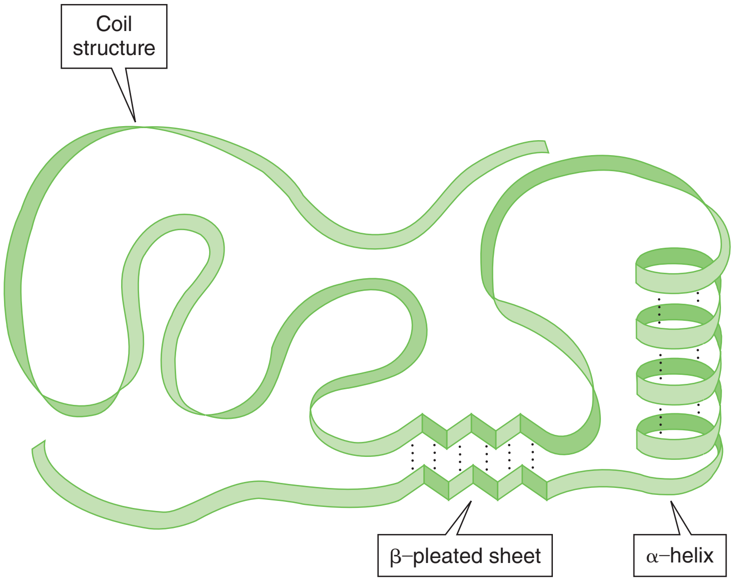


FIGURE 19.13 A segment of a protein showing areas of α-helical, β-pleated sheet, and coil molecular structure.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS 19.2

A Milk Primer

There are many different available options for milk today. There is coconut milk, almond milk, and soy milk in addition to regular dairy milk. Even dairy milk has numerous available options such as whole milk, 2%, 1%, and skim. It can be hard to decide what will be the best milk for you. To make this decision, it is important to know the differences between the kinds of milk available.

Whole milk contains 3.5% fat by weight of the milk. This means that whole milk has about 8.7 grams of saturated fat in every 8-ounce serving. In addition to the fat, whole milk also contains conjugated linoleic acid (CLA). CLA can reduce the risk of heart disease and cancer, but this benefit is reduced somewhat by the large amount of fat in whole milk. Reduced-fat, or 2%, milk has 122 calories in an 8-ounce serving. It has 5 grams of fat, but only 3 of the 5 grams are saturated fat. Low-fat, or 1%, milk has only 102 calories and 2 grams of fat per serving. Skim, or nonfat, milk contains 83 calories and little or no fat per 8-ounce serving. Skim milk has an advantage of a little more calcium per serving than other milks.

There are now milks on the market that are "omega-3-fortified." This means that the milk has 32–50 milligrams of omega-3 supplement in each 8-ounce serving. The source of the omega-3 supplement is fish or algae oil that has been added to the milk. Omega-3 is recognized as a good fat, but the amount found in these milk products is tiny when compared to the recommended daily omega-3 intake of 500 milligrams.

There are even milks available that are labeled "shelf stable." This means that they have a relatively long shelf life as indicated by their expiration dates. These types of milk are made differently than others. Regular milk is made using a high temperature, short time (HTST) pasteurization process that destroys 99.9% of the bacteria in the milk. Shelf-stable milks are pasteurized using an ultra-high temperature (UHT) process. The UHT process destroys more than the 99.9% of bacteria that is destroyed by the HTST process. This gives the milk a shelf-life of one month in shelf-stable boxes that are designed to keep oxygen and light out. The UHT process does slightly alter the milk proteins, and causes the milk to taste slightly cooked. The UHT process can also somewhat reduce the amount of vitamin B in the milk.

Burke/Triolo Productions/Getty Images

There are a number of options in the purchase of milk.

19.8 The Tertiary Structure of Proteins

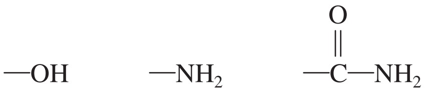
Learning Objective 8 Describe the role of side-chain interactions in the tertiary structure of proteins.

tertiary protein structure A specific three-dimensional shape of a protein resulting from interactions between R groups of the amino acid residues in the protein.

Tertiary structure, the next higher level of complexity in protein structure, refers to the bending and folding of the protein into a specific three-dimensional shape. This bending and folding may seem rather disorganized, but nevertheless it results in a favored arrangement for a given protein.

The tertiary structure results from interactions between the R side chains of the amino acid residues. These R-group interactions are of four types:

1. **Disulfide bridges:** As in the structure of insulin (see **Figure 19.9**), a disulfide linkage can form between two cysteine residues that are close to each other in the same chain or between cysteine residues in different chains. The existence and location of these disulfide bridges is a part of the tertiary structure because these interactions hold the protein chain in a loop or some other three-dimensional shape.
2. **Salt bridges:** These interactions are a result of ionic bonds that form between the ionized side chain of an acidic amino acid ($—COO^-$) and the side chain of a basic amino acid ($—NH_3^+$).
3. **Hydrogen bonds:** Hydrogen bonds can form between a variety of side chains, especially those that possess the following functional groups:



$$—OH \qquad —NH_2 \qquad —\overset{\overset{\displaystyle O}{\|}}{C}—NH_2$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

One possible interaction, between the —OH groups of two serine residues, is shown in **Figure 19.14**. We saw in **Section 19.7** that hydrogen bonding also determines the secondary structure of proteins. The distinction is that the tertiary hydrogen bonding occurs between R groups, whereas in secondary structures, the hydrogen bonding is between backbone —C=O and —N groups.

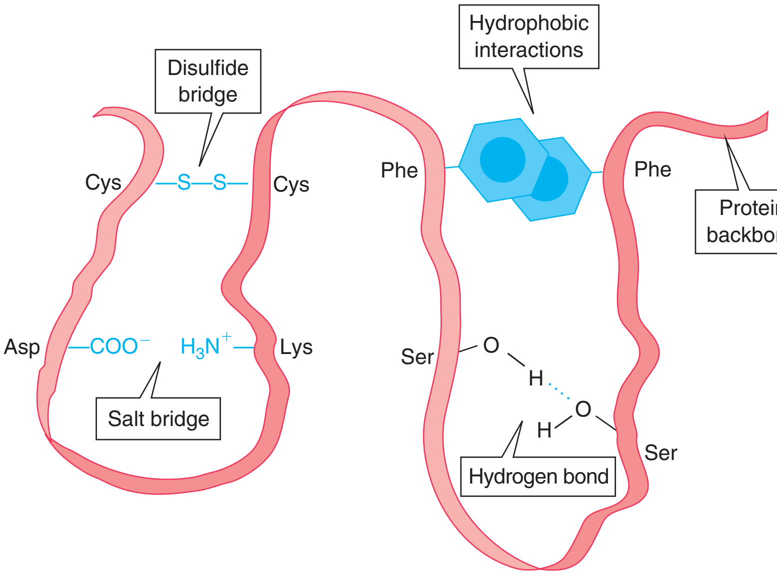


FIGURE 19.14 R-group interactions leading to tertiary protein structure.

4. **Hydrophobic interactions:** These result when nonpolar groups are either attracted to one another or forced together by their mutual repulsion of aqueous solvent. Interactions of this type are common between R groups such as the nonpolar phenyl rings of phenylalanine residues (**Figure 19.14**). This is illustrated by the compact structure of globular proteins in aqueous solutions (see **Figure 19.15**). Much like in the fatty acid micelles in **Section 18.2**, the globular shape results because polar groups are pointed outward toward the aqueous solvent, and nonpolar groups are pointed inward, away from the water molecules. This type of interaction is weaker than the other three, but it usually acts over large surface areas so that the net effect is an interaction strong enough to stabilize the tertiary structure.

The interactions leading to tertiary protein structures are summarized in **Figure 19.14**.

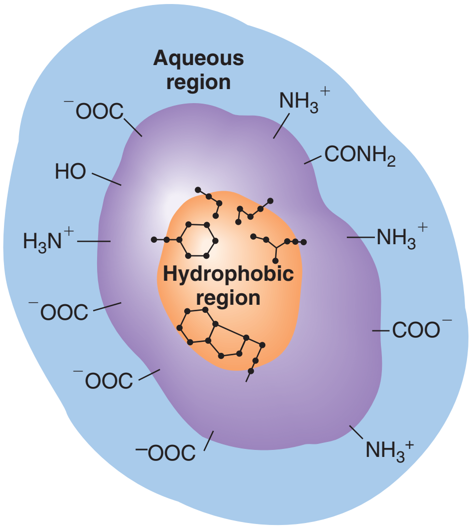
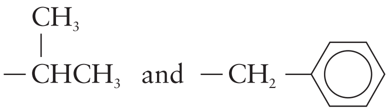


FIGURE 19.15 A globular protein with a hydrophobic region on the inside and polar groups on the outside extending into the aqueous surroundings.

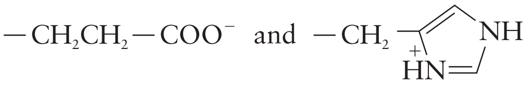
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 19.7 Identifying R-Group Interactions

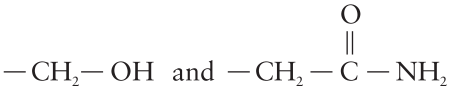
What kind of R-group interaction might be expected if the following side chains were in close proximity?

a. 

$-\overset{CH_3}{\overset{|}{C}}HCH_3$ and $-CH_2-C_6H_5$

b. 

$-CH_2CH_2-COO^-$ and $-CH_2-$

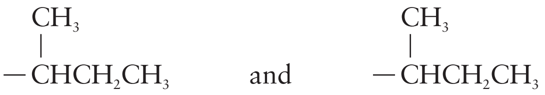
c. 

$-CH_2-OH$ and $-CH_2-\overset{O}{\overset{\|}{C}}-NH_2$

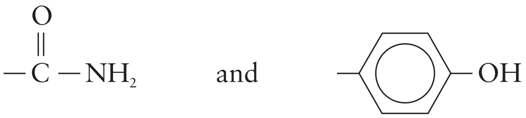
Solution

a. Hydrophobic interactions
b. Salt bridge
c. Hydrogen bonding

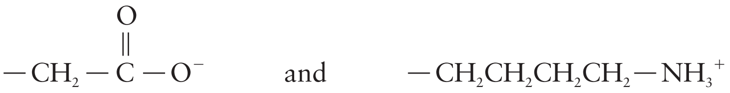
✔ **LEARNING CHECK 19.7** What kind of R-group interaction might be expected if the following side chains were in close proximity?

a. 

$-\overset{CH_3}{\overset{|}{C}}HCH_2CH_3$ and $-\overset{CH_3}{\overset{|}{C}}HCH_2CH_3$

b. 

$-\overset{O}{\overset{\|}{C}}-NH_2$ and $-C_6H_4-OH$

c. 

$-CH_2-\overset{O}{\overset{\|}{C}}-O^-$ and $-CH_2CH_2CH_2CH_2-NH_3^+$

19.9 The Quaternary Structure of Proteins

Learning Objective 9 Explain what is meant by the quaternary structure of proteins.

Many functional proteins contain two or more polypeptide chains held together by forces such as ionic attractions, disulfide bridges, hydrogen bonds, and hydrophobic forces. Each of the polypeptide chains, called **subunits**, has its own primary, secondary, and tertiary structure. The arrangement of subunits to form the larger protein is called the **quaternary structure** of the protein.

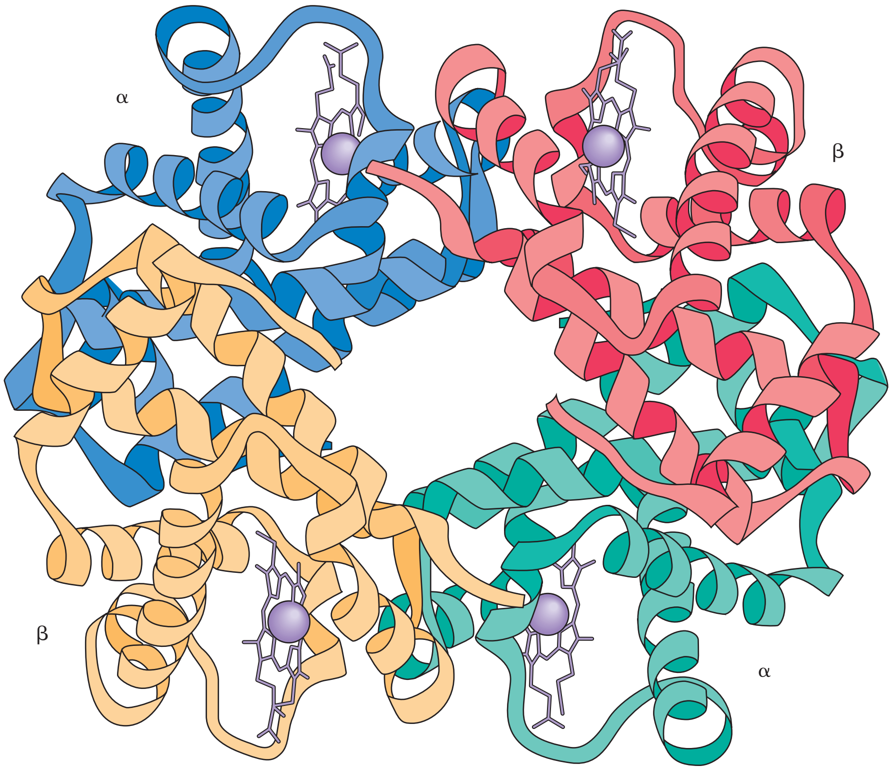
subunit A polypeptide chain having primary, secondary, and tertiary structural features that is a part of a larger protein.

quaternary protein structure The arrangement of subunits that form a larger protein.

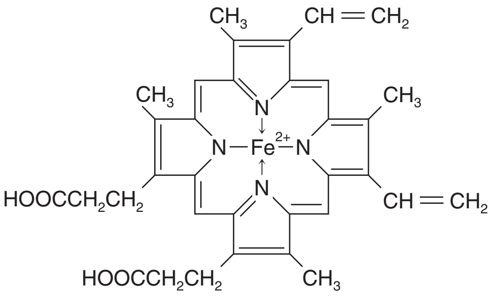
Hemoglobin is a well-known example of a protein exhibiting quaternary structure. Hemoglobin is made of four chains (subunits): two identical chains (called alpha) containing 141 amino acid residues each and two other identical chains (beta) containing 146 residues each (see **Figure 19.16a**). Each of these four hemoglobin subunits contains a heme group (a planar ring structure centered around an iron atom, shown in **Figure 19.16b**) located in crevices near the exterior of the molecule. The hemoglobin molecule is nearly spherical, with the four subunits held together rather tightly by hydrophobic forces. A schematic drawing of the quaternary structure of hemoglobin is shown in **Figure 19.16a**.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

FIGURE 19.16 The structure of hemoglobin. (a) Quaternary structure (b) Home structure



a Hemoglobin exhibits quaternary structure with two α-chains and two β-chains. The purple disks are heme groups.



b A heme group.

Example 19.8 Identifying Protein Structural Level

In what level of protein structure would you find the following features?

a. An α-helix
b. A hydrogen bond between R-groups
c. A peptide bond

Solution

a. Secondary
b. Tertiary
c. Primary

✔ **LEARNING CHECK 19.8** In what level of protein structure would you find the following features?

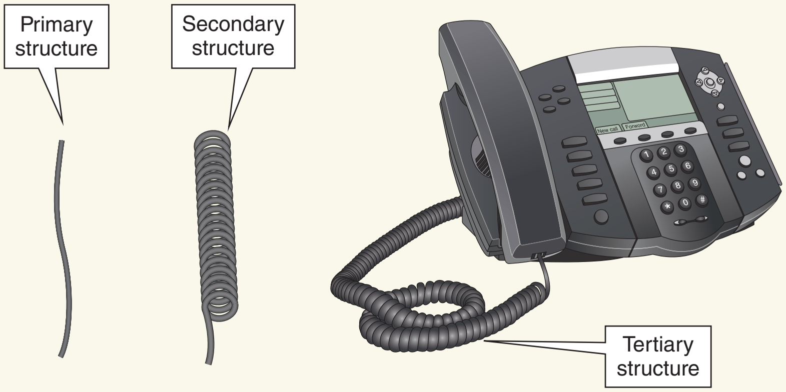
a. Intertwining of two polypeptide chains
b. β-pleated sheet
c. Hydrophobic interactions between R groups

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STUDY TOOLS 19.1

Visualizing Protein Structure

A visual aid to help you "see" protein structure and remember the difference between primary, secondary, and tertiary structure is the cord of a telephone receiver. The chainlike primary structure is represented by the long straight cord. The coiling of the cord into a helical arrangement represents the secondary structure, and the tangled arrangement the cord adopts after the receiver has been used several times is the tertiary structure.



19.10 Protein Hydrolysis and Denaturation

Learning Objective 10 Describe the conditions that can cause proteins to hydrolyze or become denatured.

native state The natural three-dimensional conformation of a functional protein.

denaturation The process by which a protein loses its characteristic native structure and function.

19.10A Hydrolysis

We learned in **Section 16.8** that amides can be hydrolyzed by an aqueous acid or base. The amide linkages of peptides and proteins also show this characteristic. As a result, the heating of a peptide or protein in the presence of an acid or base causes it to break into smaller peptides, or even amino acids, depending on the hydrolysis time, temperature, and pH.

$$\text{protein} + H_2O \xrightarrow[OH^-]{H^+ \text{ or}} \text{smaller peptides} \xrightarrow[OH^-]{H^+ \text{ or}} \text{amino acids} \quad (19.9)$$

The process of protein digestion (see **Section 22.6)** involves hydrolysis reactions that are catalyzed by enzymes in the digestive tract. In **Chapter 24**, we'll also see that the hydrolysis of cellular proteins to amino acids is an ongoing process as the body resynthesizes needed molecules and tissues.

iStock.com/DenGuy

FIGURE 19.17 An autoclave uses high-temperature steam to kill microbial life by denaturing their proteins. Autoclaves are often used in laboratory and hospital settings.

19.10B Denaturation

Proteins are maintained in their natural three-dimensional conformation, or **native state**, by stable secondary and tertiary structures and through the aggregation of subunits in quaternary structures. If proteins are exposed to physical or chemical conditions, such as extreme temperatures (see **Figure 19.17**) or pH values that disrupt these stabilizing structures, the folded native structure breaks down and the protein takes on a random, disorganized conformation (see **Figure 19.18**). This process, called **denaturation**, causes the protein to become

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

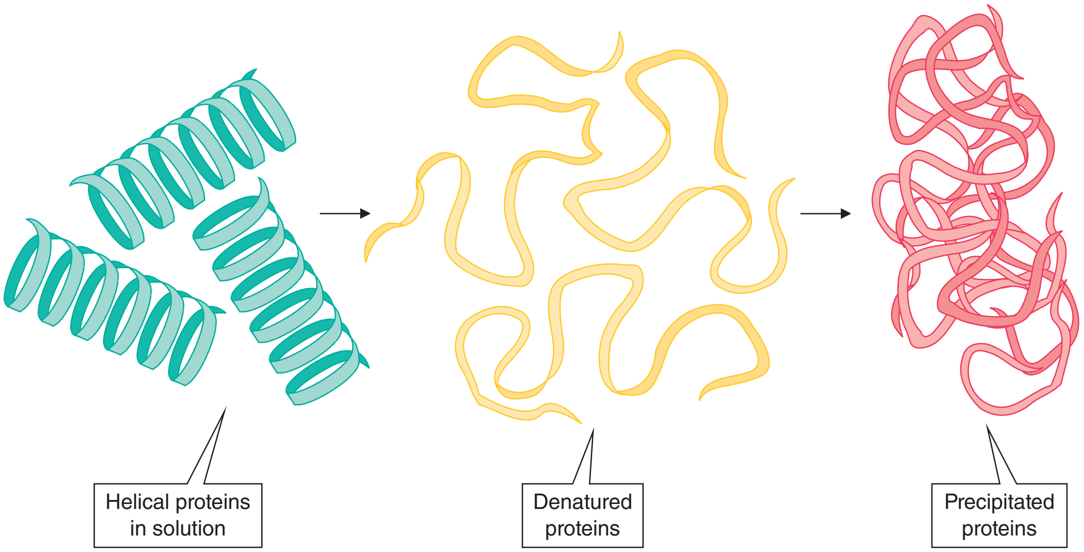


FIGURE 19.18 Protein denaturation and coagulation of the proteins.

© Christina Slabaugh

FIGURE 19.19 Denaturing the protein in eggs.

inactive, and it may precipitate because hydrophobic residues are likely to be exposed to the aqueous surroundings. The change of egg white from a clear, jellylike material to a white solid when heated is an example of this process (see **Figure 19.19**). Denaturation also explains why most proteins are biologically active only over a narrow temperature range, typically at 0–40°C. Temperatures higher than those normal for a living organism can cause intramolecular vibrations to become so intense that hydrogen bonds or other stabilizing forces are disrupted and denaturation results.

The correlation between denaturation and loss of biological activity is clearly illustrated by the common methods used to kill microorganisms and deactivate their toxins. Most bacterial toxins, which are proteins, lose their ability to cause disease when they are heated. For example, the toxic protein excreted by *Clostridium botulinum* is responsible for botulism, an often fatal form of food poisoning. This dangerous substance loses its toxic properties after being heated at 100°C for a few minutes. Heating also deactivates the toxins of the bacteria that cause diphtheria and tetanus. Heat denaturation is used to prepare vaccines against these particular diseases. The deactivated (denatured) toxin can no longer cause the symptoms of the disease to appear, but it can stimulate the body to produce substances that induce immunity to the functional toxins. It is well known that high temperatures have been used for many years in hospitals and laboratories to sterilize surgical instruments and glassware that must be germ-free. The high temperatures denature and deactivate proteins needed within the germ cells for survival.

Similar changes in protein conformation resulting in denaturation can be brought about by heavy-metal ions such as Hg^{2+}, Ag^{+}, and Pb^{2+} that interact with —SH groups and carboxylate ($—COO^{-}$) groups. Organic materials containing mercury (mercurochrome and merthiolate) were once commonly used as antiseptics in the home to treat minor skin abrasions because they denature proteins in bacteria. Mercury, silver, and lead salts are also poisonous to humans for the same reason. They deactivate critical proteins we need to live. Large doses of raw egg white and milk are often given to victims of heavy-metal poisoning. The proteins in the egg and milk bind to the metal ions and form a precipitate. The metal-containing precipitate is removed from the stomach by pumping or is ejected by induced vomiting. If the precipitated protein is not removed, it will be digested, and the toxic metal ions will be released again.

Some of the various substances and conditions that will denature proteins are summarized in **Table 19.7**.

TABLE 19.7 **Substances and Conditions That Denature Proteins**

Substance or Condition	Effect on Proteins	Examples
Heat and ultraviolet light	Disrupt hydrogen bonds and ionic attractions by making molecules vibrate too violently; produce coagulation, as in cooking an egg	Cooking food, sterilizing medical instruments
Organic solvents (ethanol and isopropyl alcohol)	Disrupt hydrogen bonds in proteins and probably form new ones with the proteins	Disinfectant used to prepare the skin for an injection
Strong acids or bases	Disrupt hydrogen bonds and ionic attractions; prolonged exposure results in hydrolysis of protein	Cheese and yogurt preparation, as lactic acid denatures milk protein
Agitation	Disrupts hydrogen bonds and hydrophobic interactions	Whipped cream and meringue
Detergents and soaps	Disrupt hydrogen bonds, hydrophobic interactions, and ionic attractions	Household soaps and detergents
Heavy metals	Form bonds to thiol groups and precipitate proteins as insoluble heavy-metal salts	Lead and mercury poisoning

Health Career Description

OPTICIAN

Opticians assist clients with eyeglasses, contacts, or other visual aids prescribed by ophthalmologists or optometrists. They work in either stand-alone clinics or in in-store clinics that sell optical products. Opticians need at least a high school diploma, but many enter the field with an associate's degree. Many states require a license to work as an optician.

According to the Bureau of Labor Statistics, "Employment of opticians is projected to grow 7 percent from 2018 to 2028, faster than the average for all occupations. An aging population and increasing rates of chronic disease are expected to lead to greater demand for corrective eyewear." The average annual income for an optician is listed as $37,840.

Opticians may be called upon to offer opinions as to how certain frames look on a client and whether they are an attractive choice. Tact, kindness, and attention to detail are important skills for the optician to possess. Ability to discern minute details and a strong understanding of fashion trends is helpful in this line of work.

Opticians work with clients of all ages, from infants to the elderly. Some eyewear is for special circumstances such as for sports, computer work, or reading magnification or for protective wear in a hazardous job. Technicians must understand specific uses for different eyewear and be able to help clients find the product that will best meet their needs. Opticians must take precise measurements of such things as interpupillary distance and determine whether bifocal or trifocal lenses are sitting at the appropriate level on the individual's face. Work as an optician demands attention to detail and precision. This is a career that is a good fit for someone who enjoys helping people.

Sources: Bergenske, P. (2002). Protein Lens Care Update Removal without Enzymes. Retrieved Apr. 26, 2020 from https://www.reviewofoptometry.com/article/lens-care-update-protein-removal-without-enzymes; Bureau of Labor Statistics. (n.d.) Opticians. Retrieved Apr. 26, from https://www.bls.gov/ooh/healthcare/opticians-dispensing.htm; Esposito, L. (2018, Sept.14).U.S News and World Report: When Contact Lenses Cause Vision Problems. Retrieved Apr. 26, 2020 from https://health.usnews.com/health-care/patient-advice/articles/2018-09-14/when-contact-lenses-cause-vision-problems

Concept Summary

19.1 The Amino Acids

Learning Objective: Can you identify the characteristic parts of alpha-amino acids?

- All proteins are polymers of amino acids, which are bifunctional organic compounds that contain both an amino group and a carboxylate group.
- Differences in the R groups of amino acids cause differences in the properties of amino acids and proteins.

19.2 Zwitterions

Learning Objective: Can you draw structural formulas to illustrate the various ionic forms assumed by amino acids?

- The presence of both amino groups and carboxyl groups in amino acids makes it possible for amino acids to exist in several ionic forms, including the form of a zwitterion.
- The zwitterion is a dipolar form in which the net charge on the ion is zero.

19.3 Reactions of Amino Acids

Learning Objective: Can you write reactions to represent the formation of peptides and proteins?

- Amino acids can undergo reactions characteristic of any functional group in the molecule.
- Two important reactions are
  - the reaction of two cysteine molecules to form a disulfide.
  - the reaction of amino groups and carboxylate groups of different molecules to form peptide (amide) linkages.

19.4 Important Peptides

Learning Objective: Can you describe uses for important peptides?

- More than 200 peptides have been shown to be essential for the proper functioning of the human body.
- Hormones are among the peptides for which functions have been identified.

19.5 Characteristics of Proteins

Learning Objective: Can you describe proteins in terms of the following characteristics: size, function, classification as fibrous or globular, and classification as simple or conjugated?

- Proteins are large polymers of amino acids.
- Acidic and basic properties of proteins are determined by the acidic or basic character of the R groups of the amino acids constituting the protein.
- Proteins perform numerous important functions in the body.
- Proteins are classified structurally as fibrous or globular.
- They are classified on the basis of composition as simple or conjugated.

19.6 The Primary Structure of Proteins

Learning Objective: Can you explain what is meant by the primary structure of proteins?

- The primary structure of a protein is the sequence of amino acids in the polymeric chain.
- This gives all proteins an identical backbone of carbon and nitrogen atoms held together by peptide linkages.
- The difference in proteins is the sequence of R groups attached to the backbone.

19.7 The Secondary Structure of Proteins

Learning Objective: Can you describe the role of hydrogen bonding in the secondary structure of proteins?

- Protein chains are held in characteristic shapes called secondary structures by hydrogen bonds.
- Two specific structures that have been identified are the α-helix and the β-pleated sheet.

19.8 The Tertiary Structure of Proteins

Learning Objective: Can you describe the role of side-chain interactions in the tertiary structure of proteins?

- A third level of complexity in protein structure results from interactions between the R groups of protein chains.
- These interactions include disulfide bridges, salt bridges, hydrogen bonds, and hydrophobic attractions.

19.9 The Quaternary Structure of Proteins

Learning Objective: Can you explain what is meant by the quaternary structure of proteins?

- Some functional proteins consist of two or more polypeptide chains held together by forces such as ionic attractions, disulfide bridges, hydrogen bonds, and hydrophobic forces.
- The arrangement of these polypeptides to form the functional protein is called the quaternary structure of the protein.

19.10 Protein Hydrolysis and Denaturation

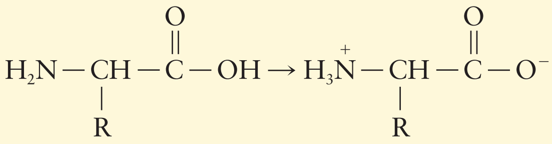
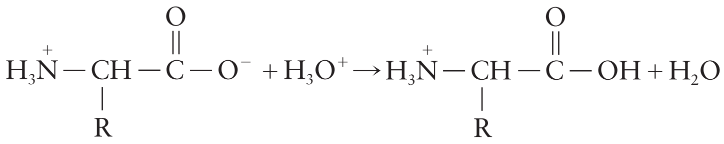
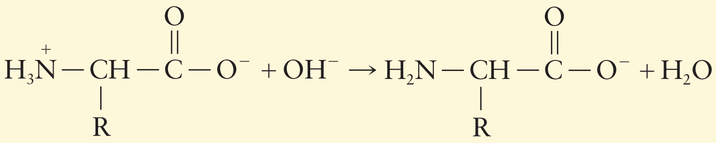
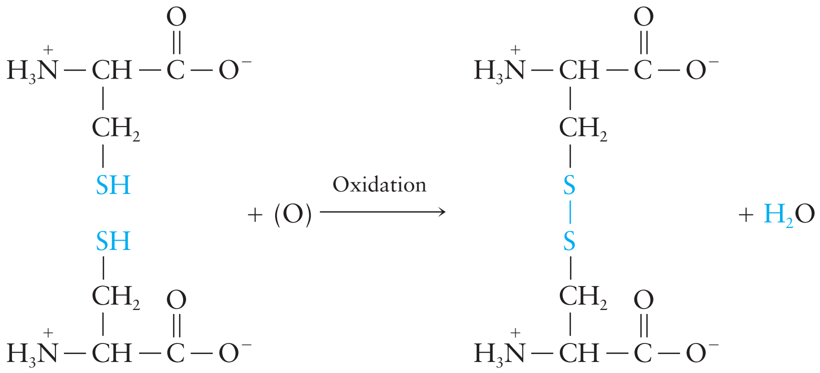
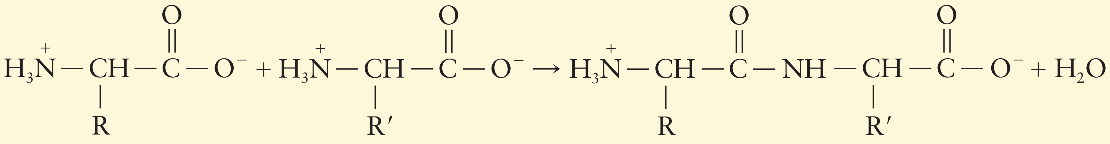
Learning Objective: Can you describe the conditions that can cause proteins to hydrolyze or become denatured?

- The peptide (amide) linkages of peptides and proteins can be hydrolyzed under appropriate conditions.
- This destroys the primary structure and produces smaller peptides or amino acids.
- The characteristic secondary, tertiary, and quaternary structures of proteins can also be disrupted by certain physical or chemical conditions such as extreme temperatures or pH values.
- The disruption of these structures is called denaturation and causes the protein to become nonfunctional and, in some cases, to precipitate.

Key Terms and Concepts

Alpha-amino acid (19.1)
α-helix (19.7)
Amino acid residue (19.3)
Antibody (19.5)
β-pleated sheet (19.7)
Conjugated protein (19.5)
C-terminal residue (19.3)
Denaturation (19.10)
Dipeptide (19.3)
Disulfide bridge (19.4)
Fibrous protein (19.5)
Globular protein (19.5)
Isoelectric point (19.2)
Native state (19.10)
N-terminal residue (19.3)
Peptide (19.3)
Peptide linkage (peptide bond) (19.3)
Polypeptide (19.3)
Primary protein structure (19.6)
Prosthetic group (19.5)
Protein (19.3)
Quaternary protein structure (19.9)
Secondary protein structure (19.7)
Simple protein (19.5)
Subunit (19.9)
Tertiary protein structure (19.8)
Zwitterion (19.2)

Key Equations

1. Formation of a zwitterion (**Section 19.2**):	 $H_2N-\underset{\underset{R}{\vert}}{CH}-\overset{\overset{O}{\Vert}}{C}-OH \rightarrow H_3\overset{+}{N}-\underset{\underset{R}{\vert}}{CH}-\overset{\overset{O}{\Vert}}{C}-O^-$	Reaction 19.1
2. Conversion of a zwitterion to a cation in an acidic solution (**Section 19.2**):	 $H_3\overset{+}{N}-\underset{\underset{R}{\vert}}{CH}-\overset{\overset{O}{\Vert}}{C}-O^- + H_3O^+ \rightarrow H_3\overset{+}{N}-\underset{\underset{R}{\vert}}{CH}-\overset{\overset{O}{\Vert}}{C}-OH + H_2O$	Reaction 19.2
3. Conversion of a zwitterion to an anion in a basic solution (**Section 19.2**):	 $H_3\overset{+}{N}-\underset{\underset{R}{\vert}}{CH}-\overset{\overset{O}{\Vert}}{C}-O^- + OH^- \rightarrow H_2N-\underset{\underset{R}{\vert}}{CH}-\overset{\overset{O}{\Vert}}{C}-O^- + H_2O$	Reaction 19.3
4. Oxidation of cysteine to cystine (**Section 19.3**):		Reaction 19.4
5. Formation of a peptide linkage—general reaction (**Section 19.3**):	 $H_3\overset{+}{N}-\underset{\underset{R}{\vert}}{CH}-\overset{\overset{O}{\Vert}}{C}-O^- + H_3\overset{+}{N}-\underset{\underset{R'}{\vert}}{CH}-\overset{\overset{O}{\Vert}}{C}-O^- \rightarrow H_3\overset{+}{N}-\underset{\underset{R}{\vert}}{CH}-\overset{\overset{O}{\Vert}}{C}-NH-\underset{\underset{R'}{\vert}}{CH}-\overset{\overset{O}{\Vert}}{C}-O^- + H_2O$	Reaction 19.6
6. Hydrolysis of proteins in acid or base (**Section 19.10**):	$\text{protein} + H_2O \xrightarrow[OH^-]{H^+ \text{ or}} \text{smaller peptides} \xrightarrow[OH^-]{H^+ \text{ or}} \text{amino acids}$	Reaction 19.9

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

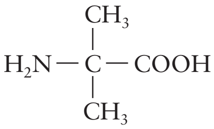
The Amino Acids (Section 19.1)

19.1 Draw the structure of hexanoic acid. Label the alpha carbon.

19.2 What functional groups are found in all amino acids?

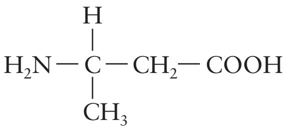
19.3 Identify which of the following are α-amino acids.

a.



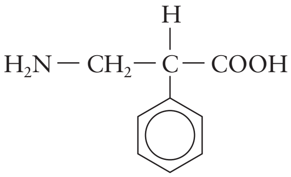
$$\begin{array}{ccc} & \mathrm{CH_3} & \\ & | & \\ \mathrm{H_2N-} & \mathrm{C} & \mathrm{-COOH} \\ & | & \\ & \mathrm{CH_3} & \end{array}$$

b.

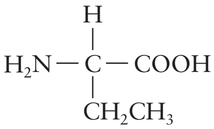


$$\begin{array}{ccc} & \mathrm{H} & \\ & | & \\ \mathrm{H_2N-} & \mathrm{C} & \mathrm{-CH_2-COOH} \\ & | & \\ & \mathrm{CH_3} & \end{array}$$

c.



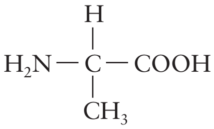
d.



$$\begin{array}{ccc} & \mathrm{H} & \\ & | & \\ \mathrm{H_2N-} & \mathrm{C} & \mathrm{-COOH} \\ & | & \\ & \mathrm{CH_2CH_3} & \end{array}$$

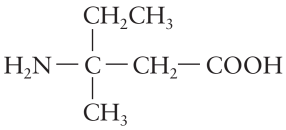
19.4 Identify which of the following are α-amino acids.

a.



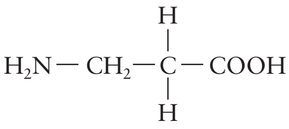
$$\begin{array}{ccc} & \mathrm{H} & \\ & | & \\ \mathrm{H_2N-} & \mathrm{C} & \mathrm{-COOH} \\ & | & \\ & \mathrm{CH_3} & \end{array}$$

b.



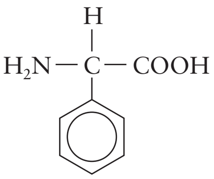
$$\begin{array}{ccc} & \mathrm{CH_2CH_3} & \\ & | & \\ \mathrm{H_2N-} & \mathrm{C} & \mathrm{-CH_2-COOH} \\ & | & \\ & \mathrm{CH_3} & \end{array}$$

c.



$$\begin{array}{ccc} & \mathrm{H} & \\ & | & \\ \mathrm{H_2N-CH_2-} & \mathrm{C} & \mathrm{-COOH} \\ & | & \\ & \mathrm{H} & \end{array}$$

d.



19.5 Identify the R group of the side chain in the following amino acids that results in the side-chain classification indicated in parentheses (see **Table 19.1**):

a. tyrosine (neutral, polar)

b. glutamate (acidic, polar)

c. methionine (neutral, nonpolar)

d. histidine (basic, polar)

19.6 Identify the R group of the side chain in the following amino acids that results in the side-chain classification indicated in parentheses (see **Table 19.1**):

a. cysteine (neutral, polar)

b. arginine (basic, polar)

c. valine (neutral, nonpolar)

d. aspartate (acidic, polar)

19.7 Draw structural formulas for the following amino acids, identify the chiral carbon atom in each one, and circle the four different groups attached to the chiral carbon.

a. threonine

b. aspartate

c. serine

d. phenylalanine

19.8 Draw structural formulas for the following amino acids, identify the chiral carbon atom in each one, and circle the four different groups attached to the chiral carbon.

a. valine

b. glutamate

c. asparagine

d. cysteine

19.9 Isoleucine contains two chiral carbon atoms. Draw the structural formula for isoleucine twice. In the first, identify one of the chiral carbons and circle the four groups attached to it. In the second, identify the other chiral carbon and circle the four groups attached to it.

19.10 Threonine contains two chiral carbon atoms. Draw the structural formula for threonine twice. In the first, identify one of the chiral carbons and circle the four groups attached to it. In the second, identify the other chiral carbon and circle the four groups attached to it.

19.11* Draw Fischer projections representing the D and L forms of the following:

a. aspartate

b. phenylalanine

19.12* Draw Fischer projections representing the D and L forms of the following:

a. serine

b. valine

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Zwitterions (Section 19.2)

19.13 What is meant by the term *zwitterion*?

19.14 What characteristics indicate that amino acids exist as zwitterions?

19.15 Draw the zwitterion structure for each of the following amino acids:

a. phenylalanine

b. glycine

c. leucine

19.16 Draw the zwitterion structure for each of the following amino acids:

a. methionine

b. threonine

c. cysteine

19.17 What is meant by the term *isoelectric point*?

19.18* Write structural formulas to show the form the following amino acids would have in a solution with a pH higher than the amino acid isoelectric point:

a. cysteine

b. alanine

19.19 Write structural formulas to show the form the following amino acids would have in a solution with a pH higher than the amino acid isoelectric point:

a. glycine

b. isoleucine

19.20* Write structural formulas to show the form the following amino acids would have in a solution with a pH lower than the amino acid isoelectric point:

a. valine

b. threonine

19.21 Write structural formulas to show the form the following amino acids would have in a solution with a pH lower than the amino acid isoelectric point:

a. methionine

b. serine

19.22 Write ionic equations to show how serine acts as a buffer against the following added ions:

a. OH^-

b. H_3O^+

19.23 Write ionic equations to show how valine acts as a buffer against the following added ions:

a. OH^-

b. H_3O^+

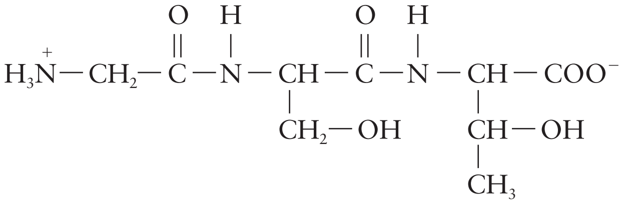
Reactions of Amino Acids (Section 19.3)

19.24 Write structural formulas to represent the formation of the two dipeptides that form when leucine and threonine react.

19.25 Write structural formulas to represent the formation of the two dipeptides that form when asparagine and glutamine react.

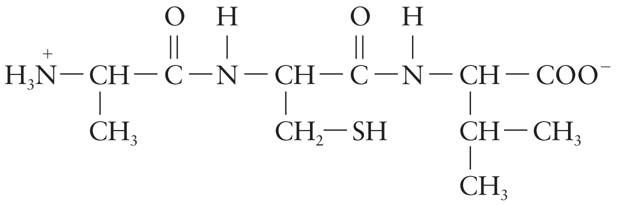
19.26 Write a complete structural formula and an abbreviated formula for the tripeptide formed from aspartate, cysteine, and valine in which the C-terminal residue is cysteine and the N-terminal residue is valine.

19.27 Identify the amino acids contained in the tripeptide below:



$$H_3\overset{+}{N}-CH_2-\overset{\overset{O}{\|}}{C}-\overset{\overset{H}{|}}{N}-\underset{\underset{CH_2-OH}{|}}{CH}-\overset{\overset{O}{\|}}{C}-\overset{\overset{H}{|}}{N}-\underset{\underset{\underset{\underset{CH_3}{|}}{CH-OH}}{|}}{CH}-COO^-$$

19.28 Identify the amino acids contained in the tripeptide below:



$$H_3\overset{+}{N}-\underset{\underset{CH_3}{|}}{CH}-\overset{\overset{O}{\|}}{C}-\overset{\overset{H}{|}}{N}-\underset{\underset{CH_2-SH}{|}}{CH}-\overset{\overset{O}{\|}}{C}-\overset{\overset{H}{|}}{N}-\underset{\underset{\underset{\underset{CH_3}{|}}{CH-CH_3}}{|}}{CH}-COO^-$$

19.29 Draw the tripeptide in Exercise 19.27 and label the N-terminal and C-terminal residues. Then, circle and label any peptide bonds.

19.30 Draw the tripeptide in Exercise 19.28 and label the N-terminal and C-terminal residues. Then, circle and label any peptide bonds.

19.31 Write a complete structural formula and an abbreviated formula for the tripeptide formed from tyrosine, serine, and phenylalanine in which the C-terminal residue is serine and the N-terminal residue is phenylalanine.

19.32 Write abbreviated formulas for the six isomeric tripeptides of alanine, phenylalanine, and arginine.

19.33 Write abbreviated formulas for the six isomeric tripeptides of asparagine, glutamate, and proline.

19.34 How many tripeptide isomers that contain one residue each of leucine, threonine, and tyrosine are possible?

19.35 How many tripeptide isomers that contain one glycine residue and two alanine residues are possible?

Important Peptides (Section 19.4)

19.36 What special role does the amino acid cysteine have in the peptides vasopressin and oxytocin?

19.37 What is the difference between a peptide and a protein?

19.38 Compare and contrast the peptide structures of vasopressin and oxytocin.

19.39 How do the biochemical functions of vasopressin and oxytocin differ?

Characteristics of Proteins (Section 19.5)

19.40 Explain why the presence of certain proteins in body fluids such as urine or blood can indicate that cellular damage has occurred in the body.

19.41* Write equations to show how a protein containing both lysine and aspartate could act as a buffer against the following added ions:

a. OH^- **b.** H_3O^+

19.42 Write equations to show how a protein containing both arginine and glutamate could act as a buffer against the following added ions:

a. OH^- **b.** H_3O^+

19.43 Explain why a protein is least soluble in an aqueous medium that has a pH equal to the isoelectric point of the protein.

19.44 Wool is a protein used as a textile fiber. Classify the protein of wool into a category of **Table 19.4**.

19.45 List the eight principal functions of proteins.

19.46 Classify each of the following proteins into one of the eight functional categories of proteins:

a. insulin

b. collagen

c. hemoglobin

d. cytochrome c

19.47 Classify each of the following proteins into one of the eight functional categories of proteins:

a. myosin

b. α-keratin

c. serum albumin

d. rhodopsin

19.48 For each of the following two proteins listed in **Table 19.4**, predict whether it is more likely to be a globular or a fibrous protein. Explain your reasoning.

a. collagen

b. lactate dehydrogenase

19.49 For each of the following two proteins listed in **Table 19.4**, predict whether it is more likely to be a globular or a fibrous protein. Explain your reasoning.

a. elastin

b. ceruloplasmin

19.50 Differentiate between simple and conjugated proteins.

19.51 Give one example of a conjugated protein that contains the following prosthetic group:

a. iron

b. lipid

c. phosphate group

d. nucleic acid

19.52 Give one example of a conjugated protein that contains the following prosthetic group:

a. carbohydrate

b. heme

c. DNA

d. zinc

The Primary Structure of Proteins (Section 19.6)

19.53 Describe what is meant by the term *primary structure of proteins.*

19.54 Explain why two polypeptides with the same amino acid composition perform different biochemical functions.

19.55 What type of bonding is present to account for the primary structure of proteins?

19.56 Write the structure for a protein backbone. Make the backbone long enough to attach four R groups symbolizing amino acid side chains.

The Secondary Structure of Proteins (Section 19.7)

19.57 Describe the differences between alpha and beta secondary structures of proteins.

19.58 Explain why two proteins that have different primary structures can form both alpha or beta secondary structures.

19.59 What type of bonding between amino acid residues is most important in holding a protein or polypeptide in a specific secondary configuration?

19.60 Describe what is meant by "supracoiling" in proteins.

The Tertiary Structure of Proteins (Section 19.8)

19.61 How do hydrogen bonds involved in tertiary protein structures differ from those involved in secondary structures?

19.62 Which amino acids have side-chain groups that can form salt bridges?

19.63* Refer to **Table 19.1** and list the type of side-chain interaction expected between the side chains of the following pairs of amino acid residues.

a. tyrosine and glutamine

b. aspartate and lysine

c. leucine and isoleucine

d. phenylalanine and valine

19.64 Refer to **Table 19.1** and list the type of side-chain interaction expected between the side chains of the following pairs of amino acid residues.

a. proline and leucine

b. glutamate and histidine

c. serine and asparagine

d. cysteine and cysteine

19.65 Refer to **Table 19.1** and identify which amino acid pairs below will *not* form R-group interactions necessary for the tertiary structure of a protein.

a. threonine and valine

b. glutamine and asparagine

c. phenylalanine and arginine

d. serine and tyrosine

19.66 Refer to **Table 19.1** and identify which amino acid pairs below will *not* form R-group interactions necessary for the tertiary structure of a protein.

a. lysine and glutamate

b. tryptophan and glutamine

c. histidine and proline

d. cysteine and methionine

19.67 Which amino acids have side-chain groups that can participate in hydrogen bonding?

19.68 A globular protein in aqueous surroundings contains the following amino acid residues: phenylalanine, methionine, glutamate, lysine, and alanine. Which amino acid side chains would be directed toward the inside of the protein and which would be directed toward the aqueous surroundings?

19.69 A globular protein in aqueous surroundings contains the following amino acid residues: proline, arginine, tyrosine, serine, and valine. Which amino acid side chains would be directed toward the inside of the protein and which would be directed toward the aqueous surroundings?

The Quaternary Structure of Proteins (Section 19.9)

19.70 What is meant by the term *quaternary protein structure*?

19.71 What types of forces give rise to quaternary structure?

19.72 Describe the quaternary protein structure of hemoglobin.

19.73 What is meant by the term *subunit*?

Protein Hydrolysis and Denaturation (Section 19.10)

19.74 What is meant by the term *denaturation*?

19.75 Suppose a sample of a protein is completely hydrolyzed and another sample of the same protein is denatured. Compare the final products of each process.

19.76 Write the primary structure of a hexapeptide containing six different amino acids if its incomplete hydrolysis yields the following peptides: Ser-Asn, Lys-Phe-Trp, Asn-Leu-Lys, Ser-Ash-Leu.

19.77 Write the primary structure of a hexapeptide containing six different amino acids if its incomplete hydrolysis yields the following peptides: Glu-His, Pro-Thr, Val-Pro, Thr-Cys-Glu.

19.78 Identify the protein structural levels (quaternary, tertiary, etc.) that are affected by the complete hydrolysis of that protein.

19.79 Identify the protein structural levels (quaternary, tertiary, etc.) that are affected by the denaturation of that protein.

19.80 Explain why drugs that are proteins, such as insulin, must always be injected rather than taken by mouth.

19.81 As fish is cooked, the tissue changes from a soft consistency to a firm one. A similar change takes place when fish is pickled by soaking it in vinegar (acetic acid). In fact, some people prepare fish for eating by pickling instead of cooking. Propose an explanation of why the two processes give somewhat similar results.

19.82 In what way is the protein in a raw egg the same as that in a cooked egg?

19.83 In addition to emulsifying greasy materials, what other useful function might be served by a detergent used to wash dishes?

19.84 Once cooked, egg whites remain in a solid form. However, egg whites that are beaten to form meringue will partially change back to a jellylike form if allowed to stand for a while. Explain these behaviors using the concept of reversible protein denaturation.

19.85 Lead is a toxic material. What form of the lead is actually the harmful substance?

19.86 Explain how egg white can serve as an emergency antidote for heavy-metal poisoning.

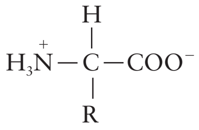
Additional Exercises

19.87 A protein has a molecular weight of about 12,000 u. This protein contains 6.4% (w/w) sulfur in the form of cystine (the cysteine disulfide). How many cystine units are present in the protein?

19.88 Which amino acids could be referred to as derivatives of butanoic acid?

19.89 A Tyndall effect is observed as light is scattered as it passes through a small polypeptide–water mixture with a pH of 6.7. What can be deduced about the polypeptide's isoelectric point from this information?

19.90 What is the conjugate acid for the following zwitterion? What is the conjugate base for it?



$$H_3\overset{+}{N}-\underset{\displaystyle R}{\overset{\displaystyle H}{C}}-COO^-$$

19.91 The K_a values recorded for alanine are 5.0×10^{-3} and 2.0×10^{-10}. Why are two values recorded? What functional groups do the values correspond to? How many K_a values would be recorded for glutamate?

Chemistry for Thought

19.92 Some researchers feel that the "high" experienced by runners may be due to the brain's synthesis of peptides. Explain why this theory might be a reasonable explanation.

19.93 Suggest a reason why individuals with the sickle-cell trait might sometimes encounter breathing problems on high-altitude flights.

19.94 In **Section 19.2**, you learned that amino acids like alanine are crystalline solids with high melting points. However, the ethyl ester of alanine, which has a free NH_2 group, melts at only 87°C. Explain why the ethyl ester melts 200 degrees below the melting point of alanine.

19.95 Why do health care workers wipe a patient's skin with solutions of rubbing alcohol before giving injections?

19.96 Would you expect plasma proteins to be fibrous or globular? Explain.

19.97 Why must the protein drug insulin be given by injection rather than taken by mouth?

19.98 In **Figure 19.8**, it is noted that animal hair is made of fibrous proteins. What properties of fibrous proteins make hair, fur, and spiderwebs useful?

19.99 Why is it necessary that protein molecules be enormous?

19.100 Name two elements that are found in proteins but are not present in fats, oils, or carbohydrates.

20 Enzymes

Kzenon/Shutterstock.com

Health Career Focus

REGISTERED NURSE

"Hello. I'll be your nurse for tonight," I said as I wrote my name on the whiteboard with a marker.

"They just took some blood," my patient informed me. "I heard something about an 'enzyme test.' What's that about?"

"Yes. Well, an enzyme is a protein that helps chemical reactions occur more quickly in the body. Levels of two enzymes in your blood, troponin T and troponin I can confirm, or rule out, a heart attack. I'm sure the doctor will consult with you as soon as those results come back."

"In the meantime, let me check on that IV, and make sure you have everything you need. I'm here for you if you need anything."

I enjoy working as an Registered nurse (RN). I especially enjoy the patient interaction. Every night is different. I like that I can answer questions, put patients at ease, and deliver important treatments. I take pride in knowing I play a vital role in the lives of my patients.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Describe the general characteristics of enzymes and explain why enzymes are vital in body chemistry. **(Section 20.1)**
2. Determine the function and/or substrate of an enzyme on the basis of its name. **(Section 20.2)**
3. Identify the general function of cofactors. **(Section 20.3)**
4. Use the lock-and-key theory to explain specificity in enzyme action. **(Section 20.4)**
5. List two ways of describing enzyme activity. **(Section 20.5)**
6. Identify the factors that affect enzyme activity. **(Section 20.6)**
7. Compare the mechanisms of competitive and noncompetitive enzyme inhibition. **(Section 20.7)**
8. Describe the three methods of cellular control over enzyme activity. **(Section 20.8)**
9. Discuss the importance of measuring enzyme levels in the diagnosis of disease. **(Section 20.9)**

THE CATALYTIC BEHAVIOR of proteins acting as enzymes is one of the most important functions performed by cellular proteins. Without catalysts, most cellular reactions would take place much too slowly to support life (see **Figure 20.1**). With the exception of a few recently discovered RNA molecules (discussed in **Chapter 21**) that catalyze their own reactions, all enzymes are globular proteins. Enzymes are the most efficient of all known catalysts; some can increase reaction rates by 10^{20} times that of uncatalyzed reactions.

© Michael Slabaugh

FIGURE 20.1 One miracle of life is that hundreds of chemical reactions take place simultaneously in each living cell; the activity of enzymes in the cells makes it all possible.

20.1 General Characteristics of Enzymes

Learning Objective 1 Describe the general characteristics of enzymes and explain why enzymes are vital in body chemistry.

Enzymes are well-suited to their essential roles in living organisms in three major ways: They have enormous catalytic power, they are highly specific in the reactions they catalyze, and their activity as catalysts can be regulated.

enzyme A biomolecule that catalyzes chemical reactions.

20.1A Catalytic Efficiency

As we know, catalysts increase the rate of chemical reactions but are not used up in the process. Although a catalyst actually participates in a chemical reaction, it is not permanently modified and may be used again and again. Enzymes are true catalysts that speed chemical reactions by lowering activation energies (see **Figure 20.2**) and allowing reactions to achieve equilibrium more rapidly.

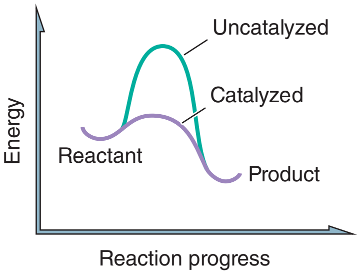


FIGURE 20.2 An energy diagram for a reaction when uncatalyzed and catalyzed.

Many of the important enzyme-catalyzed reactions are similar to the reactions we studied in the chapters on organic chemistry: ester hydrolysis, alcohol oxidation, and so on. However, laboratory conditions cannot match what happens when these reactions are carried out in the body; enzymes cause such reactions to proceed under mild pH and temperature conditions. In addition, enzyme catalysis within the body can accomplish in seconds reactions that ordinarily take weeks or even months under laboratory conditions.

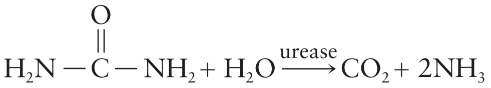
The influence of enzymes on the rates of reactions essential to life is truly amazing. A good example is the need to move carbon dioxide, a waste product of cellular respiration, out of the body. Before this can be accomplished, the carbon dioxide must be combined with water to form carbonic acid:

$$\mathrm{CO_2 + H_2O \xrightarrow[\text{}]{\substack{\text{carbonic}\\\text{anhydrase}}} H_2CO_3} \tag{20.1}$$

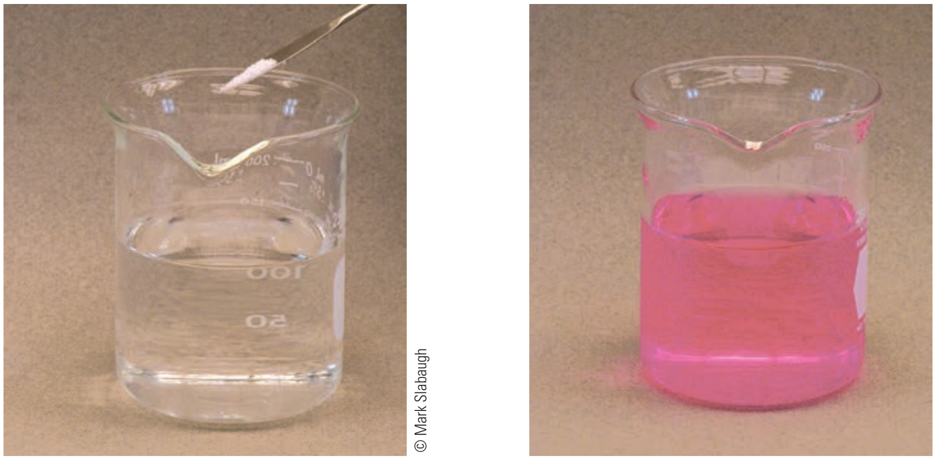
In the absence of the appropriate enzyme, carbonic anhydrase, the formation of carbonic acid takes place much too slowly to support the required exchange of carbon dioxide between the blood and the lungs. But in the presence of carbonic anhydrase, this vital reaction proceeds rapidly. Each molecule of the enzyme can catalyze the formation of carbonic acid at the rate of 36 million molecules per minute.

20.1B Specificity

Enzyme specificity is a second characteristic that is important in life processes. Unlike other catalysts, enzymes are often quite specific in the type of reaction they catalyze and even the particular substance that will be involved in the reaction. For example, strong acids catalyze the hydrolysis of any amide, the dehydration of any alcohol, and a variety of other processes. However, the enzyme urease catalyzes only the hydrolysis of a single amide, urea (Reaction 20.2 and **Figure 20.3**):



$$H_2N-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2 + H_2O \xrightarrow{\text{urease}} CO_2 + 2NH_3 \qquad (20.2)$$



© Mark Slabaugh

© Mark Slabaugh

1 The enzyme urease is added to a urea solution containing the indicator phenolphthalein.

2 As urea is hydrolyzed, forming ammonia, the indicator turns pink. How else might the presence of ammonia be detected?

FIGURE 20.3 The hydrolysis of urea catalyzed by urease.

absolute specificity The characteristic of an enzyme that it acts on one and only one substance.

relative specificity The characteristic of an enzyme that it acts on several structurally related substances.

stereochemical specificity The characteristic of an enzyme that it is able to distinguish between stereoisomers.

This is an example of **absolute specificity**, the catalyzing of the reaction of one and only one substance. Other enzymes display **relative specificity** by catalyzing the reaction of structurally related substances. For example, the lipases hydrolyze lipids, proteases split up proteins, and phosphatases hydrolyze phosphate esters. **Stereochemical specificity** extends even to enantiomers: D-amino acid oxidase will not catalyze the reactions of L-amino acids.

20.1C Regulation

A third significant property of enzymes is that their catalytic behavior can be regulated. Even though each living cell contains thousands of different molecules that could react with each other in an almost unlimited number of ways, only a relatively small number of these possible reactions take place because of the enzymes present. The cell controls the rates of these reactions and the amount of any given product formed by regulating the action of the enzymes.

20.2 Enzyme Nomenclature and Classification

Learning Objective 2 Determine the function and/or substrate of an enzyme on the basis of its name.

Some of the earliest discovered enzymes were given names ending with *-in* to indicate their protein composition. For example, three of the digestive enzymes that catalyze protein hydrolysis are named pepsin, trypsin, and chymotrypsin.

The large number of enzymes now known has made it desirable to adopt a systematic nomenclature system known as the Enzyme Commission (EC) system. Enzymes are grouped into six major classes on the basis of the reaction catalyzed (see **Table 20.1**). In the EC system, each enzyme has an unambiguous (and often long) systematic name that specifies the **substrate** (substance acted on), the functional group acted on, and the type

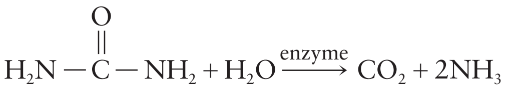
substrate The substance that undergoes a chemical change catalyzed by an enzyme.

TABLE 20.1 The EC Classification of Enzymes

Group Name	Type of Reaction Catalyzed
Oxidoreductases	Oxidation–reduction reactions
Transferases	Transfer of functional groups
Hydrolases	Hydrolysis reactions
Lyases	Addition to double bonds or the reverse of that reaction
Isomerases	Isomerization reactions
Ligases	Formation of bonds with ATP cleavage[a]

[a] ATP is discussed in **Chapter 22**.

of reaction catalyzed. All EC names end in *-ase*. The hydrolysis of urea provides a typical example:



$$H_2N-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2 + H_2O \xrightarrow{\text{enzyme}} CO_2 + 2NH_3 \qquad (20.3)$$

EC name: urea amidohydrolase
Substrate: urea
Functional group: amide
Type of reaction: hydrolysis

Enzymes are also assigned common names, which are usually shorter and more convenient. Common names are derived by adding *-ase* to the name of the substrate (see **Figure 20.4**) or to a combination of the substrate name and type of reaction. For example, urea amidohydrolase is assigned the common name urease:

Substrate: urea
Common name: urea + ase = urease

The enzyme name *alcohol dehydrogenase* is an example of a common name derived from both the name of the substrate and the type of reaction:

Substrate: alcohol (ethyl alcohol)
Reaction type: dehydrogenation (removal of hydrogen)
Common name: alcohol dehydrogenation + ase = alcohol dehydrogenase

Throughout this text, we will refer to most enzymes by their accepted common names.

iStock.com/dpullman

FIGURE 20.4 The enzyme phenolase acts on the phenols present in apples to react with oxygen and produce the familiar brownish coloration. The left half of the apple has been freshly sliced, while the right half has been exposed to air (oxygen) for a few minutes.

Example 20.1 Predicting Substrates

Predict substrates for the following enzymes:

a. lactate dehydrogenase
b. penicillinase
c. esterase

Solution

Common names for enzymes are often based on the substrate name or type of reaction plus the ending *-ase*.

a. lactate
b. penicillin
c. ester

✔ LEARNING CHECK 20.1 Predict the substrates for the following enzymes:

a. maltase
b. peptidase
c. glucose 6-phosphate isomerase

HEALTH CONNECTIONS **20.1**

Cut Back on Processed Meat

Dietary guidelines continue to change in accordance with research-based evidence. A panel of experts convened by the World Health Organization (WHO) and the International Agency for Research on Cancer (IARC) concluded in December of 2015 that eating processed meats such as hot dogs, lunch meat, salami, ham, pepperoni, and bacon increased the risk of developing colon cancer. This was disturbing news for many Americans.

The IARC panel defined processed meats as those "transformed through salting, curing, fermentation, smoking, or other processes to enhance flavor or improve preservation."

The risk of eating processed and red meat comes not only from the food itself, but also from the cooking method used. Cooking at high temperatures or in direct contact with a flame (as in roasting a hot dog over a fire or grilling a steak) can produce certain substances that are known to be carcinogenic. For example, high-temperature meat cooking produces heterocyclic amines (HCA) and polycyclic aromatic hydrocarbons (PAH). Both of these substances have been shown to cause cancer in animals.

How much processed or red meat poses a health risk? Or, how much can one person consume safely? The new report indicates that eating 50 grams of processed meat per day increases the chances of developing colorectal cancer by 18%. To be clear, this means that the risk of developing cancer increases from an existing lifetime risk of 5% for those who do not consume these products to a lifetime risk of 6% for those that do. Fifty grams of processed meat is equivalent to one of the following: 1 hot dog, 5 slices of salami, 2 slices of Canadian bacon, or 2 slices of ham.

Does this mean no more of your favorite party foods? Experts, not involved in the report, suggest that people should moderate their intake of processed meats and maintain that the increased risk of cancer from eating processed meats is relatively small.

philippou/Shutterstock.com

Hot dogs, lunch meat, and salami are typical processed meats.

20.3 Enzyme Cofactors

Learning Objective 3 Identify the general function of cofactors.

cofactor A nonprotein molecule or ion required by an enzyme for catalytic activity.

coenzyme An organic molecule required by an enzyme for catalytic activity.

apoenzyme A catalytically inactive protein formed by removal of the cofactor from an active enzyme.

In **Section 19.5**, we learned that proteins may be simple (containing only amino acid residues) or conjugated with a prosthetic group present. Many enzymes are simple proteins, whereas many others function only in the presence of specific nonprotein molecules or metal ions. If these nonprotein components are tightly bound to and form an integral part of the enzyme structure, they are true prosthetic groups. Often, however, a nonprotein component is only weakly bound to the enzyme and is easily separated from the protein structure. This type of nonprotein component is referred to as a **cofactor**. When the cofactor is an organic substance, it is called a **coenzyme**. The cofactor may also be an inorganic ion (usually a metal ion). The protein portion of enzymes requiring a cofactor is called the **apoenzyme**. Thus, the combination of an apoenzyme and a cofactor produces an active enzyme:

$$\text{apoenzyme} + \text{cofactor (coenzyme or inorganic ion)} \rightarrow \text{active enzyme} \qquad (20.4)$$

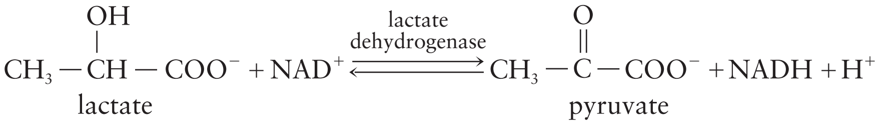
Typical inorganic ions are metal ions such as Mg^{2+}, Zn^{2+}, and Fe^{2+}. For example, the enzyme carbonic anhydrase functions only when Zn^{2+} is present, and rennin needs Ca^{2+} in order to curdle milk. Numerous other metal ions are essential for proper enzyme function in humans; hence, they are required for good health.

Like metal ions, the small organic molecules that act as coenzymes bind reversibly to an enzyme and are essential for its activity. An interesting feature of coenzymes is that many of them are formed in the body from vitamins (see **Table 20.2**), which explains why it is necessary to have certain vitamins in the diet for good health. For example, the coenzyme nicotinamide adenine dinucleotide (NAD^+), which is a necessary part of some enzyme-catalyzed oxidation–reduction reactions, is formed from the vitamin precursor

TABLE 20.2 Vitamins and Their Coenzyme Forms

Vitamin	Coenzyme Form	Function
Biotin	biocytin	Carboxyl group removal or transfer
Folacin	tetrahydrofolic acid	One-carbon group transfer
Lipoic acid	lipoamide	Acyl group transfer
Niacin (Vitamin B_3)	nicotinamide adenine dinucleotide (NAD^+)	Hydrogen transfer
	nicotinamide adenine dinucleotide phosphate ($NADP^+$)	Hydrogen transfer
Pantothenic acid	coenzyme A (CoA)	Acyl group carrier
Pyridoxal, pyridoxamine, pyridoxine (B_6 group)	pyridoxal phosphate	Amino group transfer
Riboflavin (Vitamin B_2)	flavin mononucleotide (FMN) flavin adenine dinucleotide (FAD)	Hydrogen transfer Hydrogen transfer
Thiamin (Vitamin B_1)	thiamin pyrophosphate (TPP)	Aldehyde group transfer
Cyanocobalamin (Vitamin B_{12})	methylcobalamin or deoxyadenoxylcobalamin	Shift of hydrogen atoms between adjacent carbon atoms; methyl group transfer

nicotinamide (see **Figure 20.5**). Reaction 20.5 shows the participation of NAD^+ in the oxidation of lactate by the enzyme lactate dehydrogenase (LDH). Like other cofactors, NAD^+ is written separately from the enzyme so that the change in its structure may be shown and to emphasize that the enzyme and cofactor are easily separated.



$$\underset{\text{lactate}}{CH_3-\overset{\overset{\displaystyle OH}{|}}{CH}-COO^-} + NAD^+ \xrightleftharpoons[]{\text{lactate dehydrogenase}} \underset{\text{pyruvate}}{CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-COO^-} + NADH + H^+ \qquad (20.5)$$

We can see from the reaction that the coenzyme NAD^+ is essential because it is the actual oxidizing agent. NAD^+ is typical of coenzymes that often aid in the transfer of chemical groups from one compound to another. In Reaction 20.5, NAD^+ accepts hydrogen from lactate and will transfer it to other compounds in subsequent reactions. In **Chapter 22**, we will discuss in greater detail several coenzymes that act as shuttle systems in the exchange of chemical substances among various biochemical pathways.

SOLARAY
DIETARY SUPPLEMENT
Niacinamide
500 mg
with Aloe Vera
100 VegCaps

Carlos Yudica/Shutterstock.com

FIGURE 20.5 Nicotinamide, or niacinamide, is a water-soluble form of vitamin B_3.

20.4 The Mechanism of Enzyme Action

Learning Objective 4 Use the lock-and-key theory to explain specificity in enzyme action.

Although enzymes differ widely in structure and specificity, a general theory has been proposed to account for their catalytic behavior. Because enzyme molecules are large compared with the molecules whose reactions they catalyze (substrate molecules), it has been proposed that substrate and enzyme molecules come in contact and interact over only a small region of the enzyme surface. This region of interaction is called the **active site**.

active site The location on an enzyme where a substrate is bound and catalysis occurs.

The binding of a substrate molecule to the active site of an enzyme may occur through hydrophobic attraction, hydrogen bonding, and/or ionic bonding. The complex formed when a substrate and an enzyme bond is called the enzyme–substrate (ES) complex. Once this complex is formed, the conversion of substrate (S) to product (P) may take place:

General reaction:

$$\underset{\text{enzyme}}{E} + \underset{\text{substrate}}{S} \rightleftharpoons \underset{\text{enzyme–substrate complex}}{ES} \longrightarrow \underset{\text{enzyme}}{E} + \underset{\text{product}}{P} \qquad (20.6)$$

Specific example:

$$\underset{\text{enzyme}}{\text{sucrase}} + \underset{\text{substrate}}{\text{sucrose}} \rightleftarrows \left\{\begin{matrix}\text{sucrase–}\\ \text{sucrose}\\ \text{complex}\end{matrix}\right\} \longrightarrow \underset{\text{enzyme}}{\text{sucrase}} + \underset{\text{products}}{\text{glucose} + \text{fructose}} \tag{20.7}$$

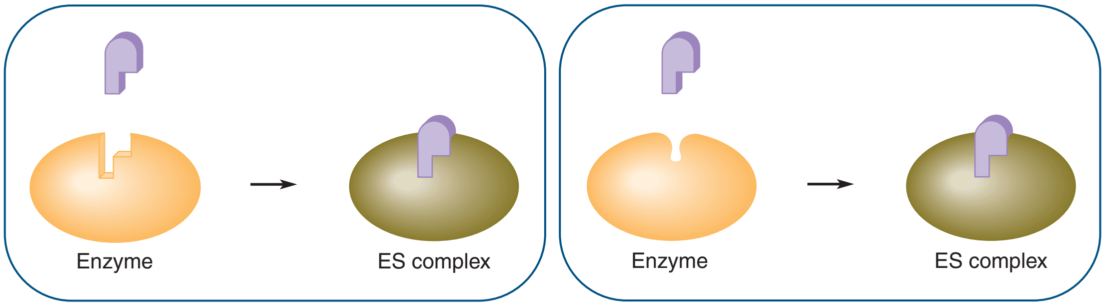
The chemical transformation of the substrate occurs at the active site, usually aided by enzyme functional groups that participate directly in the making and breaking of chemical bonds. After chemical conversion has occurred, the product is released from the active site, and the enzyme is free for another round of catalysis.

lock-and-key theory A theory of enzyme specificity proposing that a substrate has a shape fitting that of the enzyme's active site, as a key fits a lock.

An extension of the theory of ES complex formation is used to explain the high specificity of enzyme activity. According to the **lock-and-key theory**, enzyme surfaces will accommodate only those substrates having specific shapes and sizes. Thus, only specific substrates "fit" a given enzyme and can form complexes with it (see **Figure 20.6a**).

induced-fit theory A theory of enzyme action proposing that the conformation of an enzyme changes to accommodate an incoming substrate.

A limitation of the lock-and-key theory is the implication that enzyme conformations are fixed or rigid. However, research results suggest that the active sites of some enzymes are not rigid. This is taken into account in a modification of the lock-and-key theory known as the **induced-fit theory**, which proposes that enzymes have somewhat flexible conformations that may adapt to incoming substrates. The active site has a shape that becomes complementary to that of the substrate only after the substrate is bound (see **Figure 20.6b**).



a In the **lock-and-key model**, the rigid enzyme and substrate have matching shapes.

b In the **induced-fit model**, the flexible enzyme changes shape to match the substrate.

FIGURE 20.6 Models representing enzyme action.

20.5 Enzyme Activity

Learning Objective 5 List two ways of describing enzyme activity.

enzyme activity The rate at which an enzyme catalyzes a reaction.

turnover number The number of molecules of substrate acted on by one molecule of enzyme per minute.

Enzyme activity refers in general to the catalytic ability of an enzyme to increase the rate of a reaction. The amazing rate (36 million molecules per minute) at which one molecule of carbonic anhydrase converts carbon dioxide to carbonic acid was mentioned earlier. This rate, called the **turnover number**, is one of the highest known for enzyme systems. More common turnover numbers for enzymes are closer to 10^3/min, or 1000 reactions per minute. Nevertheless, even such low numbers dramatize the speed with which a small number of enzyme molecules can transform a large number of substrate molecules. **Table 20.3** gives the turnover numbers of several enzymes.

Experiments that measure enzyme activity are called *enzyme assays*. Assays for blood enzymes are routinely performed in clinical laboratories. Such assays are often done by determining how fast the characteristic color of a product forms or the color of a substrate decreases. Reactions in which protons (H^+) are produced or used up can be followed by measuring how fast the pH of the reacting mixture changes with time.

enzyme international unit (IU) A quantity of enzyme that catalyzes the conversion of 1 μmol of substrate per minute under specified conditions.

Because some clinical assays are done many times a day, the procedures for running the assays have been automated and computerized. The determined enzyme activity levels are usually reported in terms of **enzyme international units (IU)**, which define enzyme activity as the amount of enzyme that will convert a specified amount of substrate to a product within a certain time.

TABLE 20.3 Examples of Enzyme Turnover Numbers

Enzyme	Turnover Number (per minute)	Reaction Catalyzed
Carbonic anhydrase	36,000,000	$CO_2 + H_2O \rightleftharpoons H_2CO_3$
Catalase	5,600,000	$2H_2O_2 \rightleftharpoons 2H_2O + O_2$
Cholinesterase	1,500,000	Hydrolysis of acetylcholine
Chymotrypsin	6,000	Hydrolysis of specific peptide bonds
DNA polymerase I	900	Addition of nucleotide monomers to DNA chains
Lactate dehydrogenase	60,000	pyruvate + NADH + $H^+ \rightleftharpoons$ lactate + NAD^+
Penicillinase	120,000	Hydrolysis of penicillin

One standard enzyme international unit (1 IU) is the quantity of enzyme that catalyzes the conversion of 1 micromole (μmol) of substrate per minute under specified reaction conditions. Thus, unlike the turnover number, which is a constant characteristic for one molecule of a particular enzyme, international units measure how much enzyme is present. For example, an enzyme preparation with an activity corresponding to 40 IU contains a concentration of enzyme 40 times greater than the standard. This is a useful way to measure enzyme activity because the level of enzyme activity compared with normal activity is significant in the diagnosis of many diseases (see **Section 20.9**).

Example 20.2 Describing Enzyme Activity

List two ways of describing enzyme activity.

Solution

Turnover number and enzyme international unit.

✔ **LEARNING CHECK 20.2** Differentiate between the terms *turnover number* and *enzyme international unit.*

20.6 Factors Affecting Enzyme Activity

Learning Objective 6 Identify the factors that affect enzyme activity.

Several factors affect the rate of enzyme-catalyzed reactions (see **Figure 20.7**). The most important factors are enzyme concentration, substrate concentration, temperature, and pH. In this section, we'll look at each of these factors in some detail. In **Section 20.7**, we'll consider another very important factor, the presence of enzyme inhibitors.

20.6A Enzyme Concentration

In an enzyme-catalyzed reaction, the concentration of enzyme is normally very low compared with the concentration of substrate. When the enzyme concentration is increased, the concentration of ES also increases in compliance with reaction rate theory:

$$E + S \rightleftarrows ES$$
$$\text{increased [E] gives more [ES]}$$

Thus, the availability of more enzyme molecules to catalyze a reaction leads to the formation of more ES and a higher reaction rate. The effect of enzyme concentration on the

PF-(bygone1)/Alamy Stock Photo

FIGURE 20.7 Maud Menten, a biomedical researcher, made significant contributions to the field of mathematics dealing with the rate of enzyme-catalyzed reactions by co-authoring the Michaelis–Menten equation in 1913.

rate of a reaction is shown in **Figure 20.8**. As the figure indicates, the rate of a reaction is directly proportional to the concentration of the enzyme—that is, if the enzyme concentration is doubled, the rate of conversion of substrate to product is also doubled.

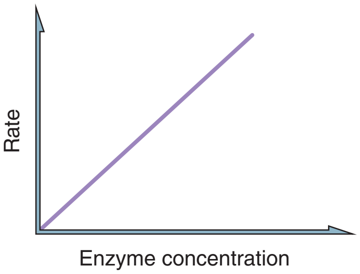


FIGURE 20.8 The dependence of reaction rate (initial velocity) on enzyme concentration.

20.6B Substrate Concentration

As shown in **Figure 20.9**, the concentration of substrate significantly influences the rate of an enzyme-catalyzed reaction. Initially, the rate is responsive to increases in substrate concentration. However, at a certain concentration, the rate levels out and remains constant. This maximum rate (symbolized by $V_{\max}$) occurs because the enzyme is saturated with substrate and cannot work any faster under the conditions imposed.

20.6C Temperature

optimum temperature The temperature at which enzyme activity is highest.

Enzyme-catalyzed reactions, like all chemical reactions, have rates that increase with temperature (see **Figure 20.10**). However, because enzymes are proteins, there is a temperature limit beyond which the enzyme becomes vulnerable to denaturation. Thus, every enzyme-catalyzed reaction has an **optimum temperature**, usually in the range of 25°C–40°C. Above or below that value, the reaction rate will be lower. This effect is illustrated in **Figure 20.10**.

20.6D The Effect of pH

The graph of enzyme activity as a function of pH is somewhat similar to the behavior as a function of temperature (see **Figure 20.11**). Notice in **Figure 20.11** that an enzyme is most effective in a narrow pH range and is less active at pH values lower or higher than this optimum. This variation in enzyme activity with changing pH may be due to the influence of pH on acidic and basic side chains within the active site. In addition, most enzymes are denatured by pH extremes. The resistance of pickled foods (see **Figure 20.12**) to spoilage is due to the enzymes of microorganisms being less active under acidic conditions.

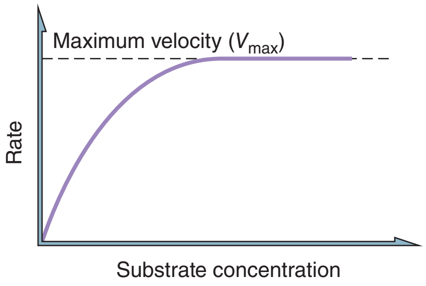


FIGURE 20.9 The dependence of reaction rate (initial velocity) on substrate concentration.

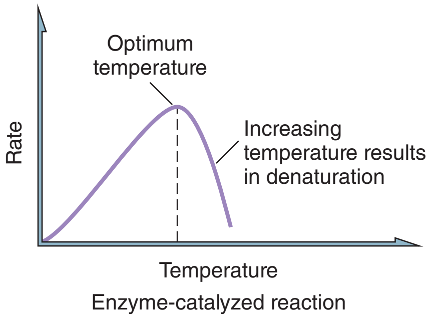


FIGURE 20.10 The effect of temperature on enzyme-catalyzed reaction rates.

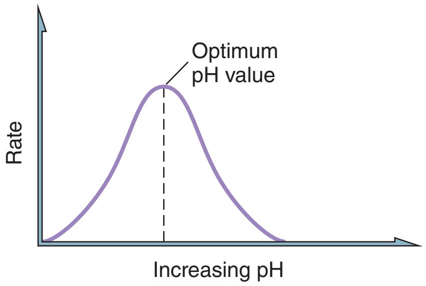


FIGURE 20.11 A typical plot of the effect of pH on reaction rate.

skyradar/20 images/Pixabay

FIGURE 20.12 Pickles are prepared under acidic conditions. Why do they resist spoilage?

Many enzymes have an **optimum pH** near 7, the pH of most biological fluids. However, the optimum pH of a few is considerably higher or lower than 7. For example, pepsin, a digestive enzyme of the stomach, shows maximum activity at a pH of about 1.5, the pH of gastric fluids. **Table 20.4** lists optimum pH values for several enzymes.

optimum pH The pH at which enzyme activity is highest.

TABLE 20.4 Examples of Optimum pH for Enzyme Activity

Enzyme	Source	Optimum pH
Pepsin	Gastric mucosa	1.5
β-glucosidase	Almond	4.5
Sucrase	Intestine	6.2
Urease	Soybean	6.8
Catalase	Liver	7.0
Succinate dehydrogenase	Beef heart	7.6
Arginase	Beef liver	9.0
Alkaline phosphatase	Bone	9.5

Example 20.3 Identifying Factors Affecting Activity

List four factors that can affect enzyme activity.

Solution

Enzyme concentration, substrate concentration, temperature, and pH

✔ **LEARNING CHECK 20.3** Indicate how each of the following affects the rate of an enzyme-catalyzed reaction:

a. Increase in enzyme concentration
b. Increase in substrate concentration
c. Increase in temperature
d. Increase in pH

20.7 Enzyme Inhibition

Learning Objective 7 Compare the mechanisms of competitive and noncompetitive enzyme inhibition.

An **enzyme inhibitor** is any substance that can decrease the rate of an enzyme-catalyzed reaction. An understanding of enzyme inhibition is important for several reasons. First, the characteristic function of many poisons and some medicines is to inhibit one or more enzymes and to decrease the rates of the reactions they catalyze. Second, some substances normally found in cells inhibit specific enzyme-catalyzed reactions and thereby provide a means for the internal regulation of cellular metabolism.

enzyme inhibitor A substance that decreases the activity of an enzyme.

Enzyme inhibitors are classified into two categories, reversible and irreversible, on the basis of how they behave at the molecular level.

20.7A Irreversible Inhibition

An irreversible inhibitor forms a covalent bond with a specific functional group of the enzyme and as a result renders the enzyme inactive. A number of very deadly poisons act as irreversible inhibitors.

The cyanide ion (CN^-) is an example of an irreversible enzyme inhibitor. It is extremely toxic and acts very rapidly. The cyanide ion interferes with the operation of an iron-containing

ExplorerBob/287 images/Pixabay

FIGURE 20.13 The seeds (also known as stones or pits) of fruits like apricots, cherries, plums, and peaches contain small amounts of a compound that releases hydrogen cyanide when ingested.

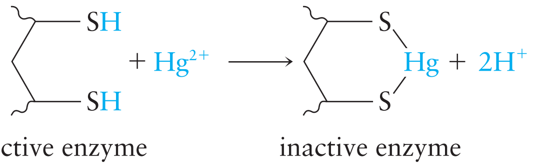
enzyme called cytochrome oxidase. The ability of cells to use oxygen depends on the action of cytochrome oxidase. When the cyanide ion reacts with the iron of this enzyme, it forms a very stable complex (see **Reaction 20.8**), and the enzyme can no longer function properly. As a result, cell respiration stops, causing death in a matter of minutes (see **Figure 20.13**).

$$\underset{\text{cytochrome oxidase}}{\text{Cyt—Fe}^{3+}} + \underset{\text{cyanide ion}}{\text{CN}^{-}} \rightarrow \underset{\text{stable complex}}{\text{Cyt—Fe—CN}^{2+}} \tag{20.8}$$

Any antidote for cyanide poisoning must be administered quickly. One antidote is sodium thiosulfate (the "hypo" form is used in the developing of photographic film). This substance converts the cyanide ion to a thiocyanate ion that does not bind to the iron of cytochrome oxidase.

$$\underset{\text{cyanide}}{\text{CN}^{-}} + \underset{\text{thiosulfate}}{\text{S}_2\text{O}_3{}^{2-}} \rightarrow \underset{\text{thiocyanate}}{\text{SCN}^{-}} + \underset{\text{sulfite}}{\text{SO}_3{}^{2-}} \tag{20.9}$$

The toxicity of heavy metals such as mercury and lead is due to their ability to render the protein part of enzymes ineffective. These metals act by combining with the —SH groups found on many enzymes (see **Reaction 20.10**). In addition, as we learned in **Chapter 19**, metals can cause nonspecific protein denaturation. Both mercury and lead poisoning can cause permanent neurological damage.



(20.10)

Heavy-metal poisoning is treated by administering chelating agents—substances that combine with the metal ions and hold them very tightly. One effective antidote is the chelating agent ethylenediaminetetraacetic acid, or EDTA, which will chelate all heavy metals except mercury.

The calcium salt of EDTA is administered intravenously. In the body, calcium ions of the salt are displaced by heavy-metal ions, such as lead, that bind to the chelate more tightly. The lead–EDTA complex is soluble in body fluids and is excreted in the urine.

$$\text{CaEDTA}^{2-} + \text{Pb}^{2+} \rightarrow \text{PbEDTA}^{2-} + \text{Ca}^{2+} \tag{20.11}$$

antibiotic A substance produced by one microorganism that kills or inhibits the growth of other microorganisms.

Not all enzyme inhibitors act as poisons toward the body; some, in fact, are useful therapeutic agents. Sulfa drugs and the group of compounds known as penicillins are two well-known families of **antibiotics** that inhibit specific enzymes essential to the life processes of bacteria. The first penicillin was discovered in 1928 by Alexander Fleming. He noticed that the bacteria on a culture plate did not grow in the vicinity of a mold that had contaminated the culture; the mold was producing penicillin. The general penicillin structure is shown in **Table 20.5**, along with four widely used forms. Penicillins interfere with transpeptidase, an enzyme that is important in bacterial cell wall construction. The inability to form strong cell walls prevents the bacteria from surviving (see **Figure 20.14**).

PENICILLIN V POTASSIUM
TABLETS FILM COATED
EQUIVALENT TO
500 mg
PENICILLIN V

Scott Camazine/Science Source

FIGURE 20.14 Penicillin is used to treat certain infections caused by bacteria such as pneumonia, strep throat, scarlet fever, and ear, skin, and mouth infections.

20.7B Reversible Inhibition

A reversible inhibitor (in contrast to one that is irreversible) reversibly binds to an enzyme. An equilibrium is established; therefore, the inhibitor can be removed from the enzyme by shifting the equilibrium:

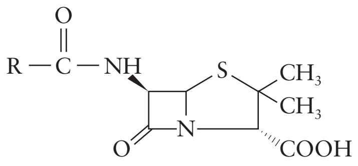
$$\text{E} + \text{I} \rightleftarrows \text{EI}$$

There are two types of reversible inhibitors: competitive and noncompetitive.

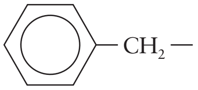
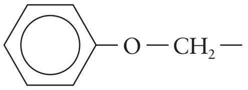
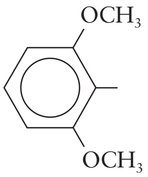
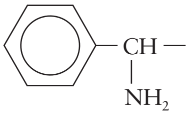
competitive inhibitor An inhibitor that competes with substrate for binding at the active site of the enzyme.

A **competitive inhibitor** binds to the active site of an enzyme and thus "competes" with substrate molecules for the active site. Competitive inhibitors often have molecular structures that are similar to the normal substrate of the enzyme. The competitive inhibi-

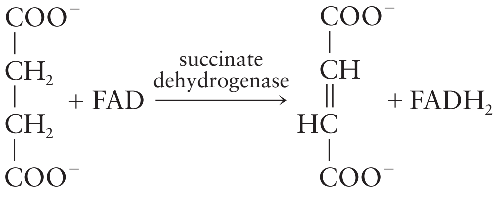
TABLE 20.5 **Four Widely Used Penicillins**



General penicillin structure

Name	Year Marketed	Side Chain (R—)	Comments
Penicillin G	1943		Usually given by injection
Penicillin V	1953		An oral penicillin; resistant to stomach hydrolysis
Methicillin	1960		Given by injection
Ampicillin	1961		Given by injection or taken orally; effective against a broad spectrum of organisms

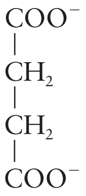
tion of succinate dehydrogenase by malonate is a classic example. Succinate dehydrogenase catalyzes the oxidation of the substrate succinate to form fumarate by transferring two hydrogens to the coenzyme FAD:



$$\begin{array}{c} COO^- \\ | \\ CH_2 \\ | \\ CH_2 \\ | \\ COO^- \end{array} + FAD \xrightarrow[\text{dehydrogenase}]{\text{succinate}} \begin{array}{c} COO^- \\ | \\ CH \\ \| \\ HC \\ | \\ COO^- \end{array} + FADH_2 \qquad (20.12)$$

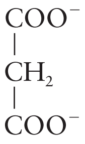
succinate fumarate

Malonate, having a structure similar to succinate, competes for the active site of succinate dehydrogenase and thus inhibits the enzyme:



$$\begin{array}{c} COO^- \\ | \\ CH_2 \\ | \\ CH_2 \\ | \\ COO^- \end{array}$$

succinate



$$\begin{array}{c} COO^- \\ | \\ CH_2 \\ | \\ COO^- \end{array}$$

malonate

The action of sulfa drugs on bacteria is another example of competitive enzyme inhibition. Folic acid, a substance needed for growth by some disease-causing bacteria, is normally synthesized within the bacteria by a chemical process that requires *p*-aminobenzoic acid. Because sulfanilamide, the first sulfa drug, resembles *p*-aminobenzoic acid and competes

HEALTH CONNECTIONS **20.2**

No Milk, Please

Lactose intolerance is a condition that causes a person to be unable to digest lactose, the natural sugar found in milk and dairy products. Thirty million Americans live with this condition today.

Lactase is a catalytic enzyme in our bodies that catalyzes the breakdown of the disaccharide lactose into the monosaccharides glucose and galactose. When people are lactose intolerant, they do not produce enough lactase enzyme to catalyze the total breakdown of all the lactose that has been ingested. As a result, some lactose passes through the small intestine and enters the large intestine where it creates digestive problems. In order to overcome the inability of the body to create enough lactase enzymes, lactose intolerant people can take lactase supplements before they eat or drink milk or dairy products. Some milk and dairy products contain the enzyme as an additive. The milk product called "Lactaid" is milk that contains added lactase enzyme to help those who are lactose intolerant.

When lactose intolerant people drink milk without adding lactase, the lactose disaccharide eventually makes its way into the large intestine and begins to cause pain and other discomfort. The bacteria in the large intestine begin to break down the lactose. When they do this, they also release gas, causing uncomfortable bloating and cramps. When lactose enters the large intestine it osmotically draws in water and causes diarrhea. The lactose also undergoes fermentation in the large intestine, and produces lactic acid, which can be detected in the stool. That is one way to test for lactose intolerance in a person. Lactose intolerance is often passed on genetically, and unfortunately, there is no known cure for the condition.

absolutimages/Shutterstock.com

Drinking milk can be painful for individuals who are lactose intolerant.

with it for the active site of the bacterial enzyme involved, it can prevent bacterial growth (see **Figure 20.15**). This is possible because the enzyme binds readily to either of these molecules. Therefore, the introduction of large quantities of sulfanilamide into a patient's body causes most of the active sites to be bound to the wrong (from the bacterial viewpoint) substrate. Thus, the synthesis of folic acid is stopped or slowed, and the bacteria are prevented from multiplying. Meanwhile, the normal body defenses work to destroy them.

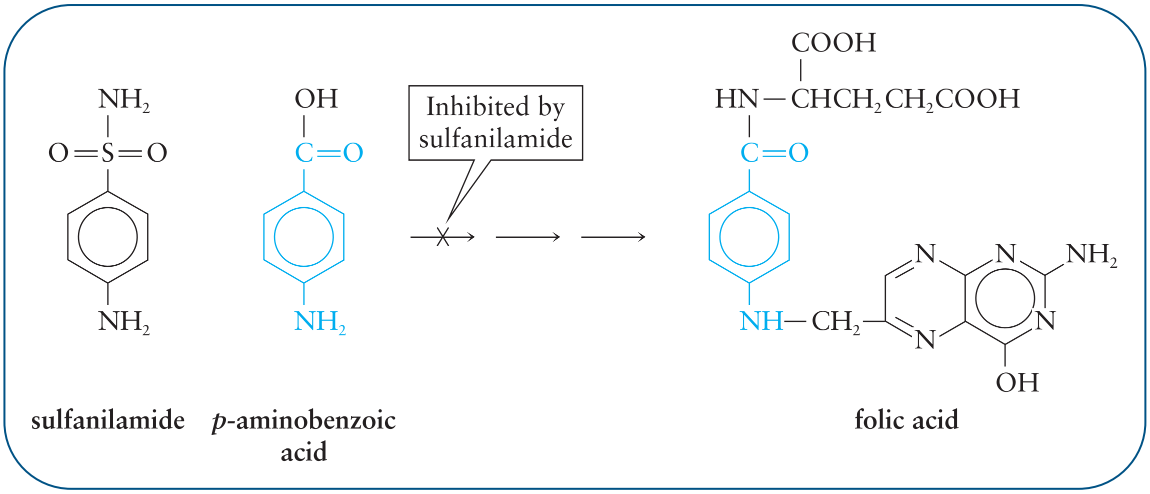


FIGURE 20.15 Structural relationships of sulfanilamide, *p*-aminobenzoic acid, and folic acid.

Human beings also require folic acid, but they get it from their diet. Consequently, sulfa drugs exert no toxic effect on humans. However, one danger of sulfa drugs, or of any antibiotic, is that excessive amounts can destroy important intestinal bacteria that perform many symbiotic, life-sustaining functions. Although sulfa drugs have largely been replaced by antibiotics such as the penicillins and tetracyclines, some are still used in treating certain bacterial infections, such as those occurring in the urinary tract.

The nature of competitive inhibition is represented in **Figure 20.16**. There is competition between the substrate and the inhibitor for the active site. Once the inhibitor combines with the enzyme, the active site is blocked, preventing further catalytic action.

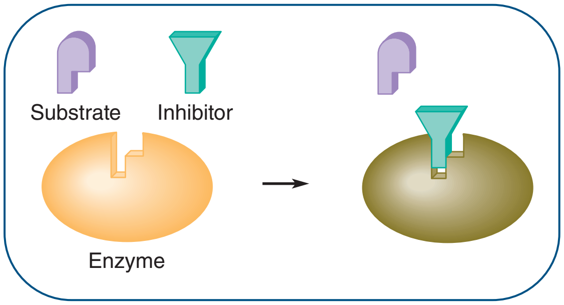


FIGURE 20.16 The behavior of competitive inhibitors. The active site is occupied by the inhibitor, and the substrate is prevented from bonding.

Competitive inhibition can be reversed by increasing the concentration of substrate and letting Le Châtelier's principle operate. This is illustrated by the following equilibria that would exist in a solution containing enzyme (E), substrate (S), and competitive inhibitor (I):

$$\text{equilibrium 1:} \quad E + S \overset{\xrightarrow{\text{Increasing [S]}}}{\rightleftharpoons} ES$$

$$\text{equilibrium 2:} \quad E + I \underset{\xleftarrow[\text{Decreasing [E]}]{}}{\rightleftharpoons} EI$$

If the concentration of substrate is increased, then according to Le Châtelier's principle, equilibrium 1 should shift to the right. As it does, the concentration of enzyme decreases, which causes equilibrium 2 to shift to the left. The overall effect is that the concentration of ES has increased while the concentration of EI has decreased. Thus, the competition between inhibitor and substrate is won by whichever molecular species is in greater concentration.

A **noncompetitive inhibitor** bears no resemblance to the normal enzyme substrate and binds reversibly to the surface of an enzyme at a site other than the catalytically active site (see **Figure 20.17**). The interaction between the enzyme and the noncompetitive inhibitor causes the three-dimensional shape of the enzyme and its active site to change. The enzyme no longer binds the normal substrate, or the substrate is improperly bound in a way that prevents the catalytic groups of the active site from participating in catalyzing the reaction.

noncompetitive inhibitor An inhibitor that binds to the enzyme at a location other than the active site.

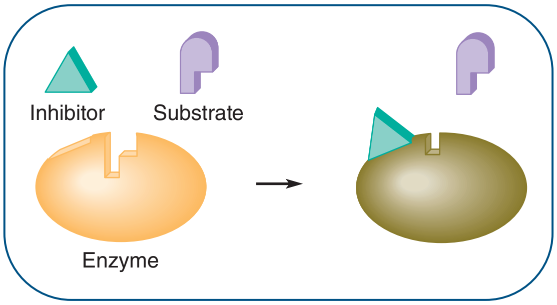


FIGURE 20.17 The behavior of noncompetitive inhibitors. The inhibitor bonds to the enzyme at a site other than the active site and changes the shape of the active site.

Unlike competitive inhibition, noncompetitive inhibition cannot be reversed by the addition of more substrate because additional substrate has no effect on the enzyme-bound inhibitor (it can't displace the inhibitor because it can't bond to the site occupied by the inhibitor).

Example 20.4 Classifying Enzyme Inhibitors

List two categories of enzyme inhibitors. For one of those categories, also list two types of inhibitors.

Solution

The two categories are reversible and irreversible. Reversible enzyme inhibitors are of two types: competitive and noncompetitive.

✔ **LEARNING CHECK 20.4** Compare a noncompetitive and a competitive inhibitor with regard to the following:

a. Resemblance to substrate
b. Binding site on the enzyme
c. The effect of increasing substrate concentration

20.8 The Regulation of Enzyme Activity

Learning Objective 8 Describe the three methods of cellular control over enzyme activity.

Enzymes work together in an organized yet complicated way to facilitate all the biochemical reactions needed by a living organism. For an organism to respond to changing conditions and cellular needs, very sensitive controls over enzyme activity are required. We will discuss three mechanisms by which this is accomplished: activation of zymogens, allosteric regulation, and genetic control.

20.8A The Activation of Zymogens

zymogen or proenzyme The inactive precursor of an enzyme.

A common mechanism for regulating enzyme activity is the synthesis of enzymes in the form of inactive precursors called **zymogens** or **proenzymes.** Some enzymes in their active form would degrade the internal structures of the cells and, ultimately, the cells themselves. Such enzymes are synthesized and stored as zymogens. When the active enzyme is needed, the stored zymogen is released from storage and activated at the location of the reaction. Activation usually involves the cleavage of one or more peptide bonds of the zymogen. The digestive enzymes pepsin, trypsin, and chymotrypsin and several of the enzymes involved in blood clotting are produced and activated this way. Trypsinogen, the inactive form of trypsin, is synthesized in the pancreas and activated in the small intestine by the hydrolysis of a single peptide bond. The products are the active enzyme (trypsin) and a hexapeptide:

$$\text{trypsinogen} + H_2O \xrightarrow{\text{enteropeptidase}} \text{trypsin} + \text{hexapeptide} \qquad (20.13)$$

Several examples of zymogens are listed in **Table 20.6**.

TABLE 20.6 Examples of Zymogens

Zymogen	Active Enzyme	Function
Chymotrypsinogen	chymotrypsin	Digestion of proteins
Pepsinogen	pepsin	Digestion of proteins
Procarboxypeptidase	carboxypeptidase	Digestion of proteins
Proelastase	elastase	Digestion of proteins
Prothrombin	thrombin	Blood clotting
Trypsinogen	trypsin	Digestion of proteins

20.8B Allosteric Regulation

A second method of enzyme regulation involves the combination of the enzyme with some other compound such that the three-dimensional conformation of the enzyme is altered and its catalytic activity is changed. Compounds that alter enzymes this way are called **modulators** of the activity; they may increase the activity (activators) or decrease the activity (inhibitors). The noncompetitive inhibitors we studied in **Section 20.7** are examples of modulators. Enzymes that have a quaternary protein structure with distinctive binding sites for modulators are referred to as **allosteric enzymes**. These variable-rate enzymes are often located at key control points in cellular processes. In general, **activators** act as signals for increased production, whereas inhibitors are used to stop the formation of excess products.

An excellent example of allosteric regulation—the control of an allosteric enzyme—is the five-step synthesis of the amino acid isoleucine (see **Figure 20.18**). Threonine deaminase, the enzyme that catalyzes the first step in the conversion of threonine to isoleucine, is subject to inhibition by the final product, isoleucine. The structures of isoleucine and threonine are quite different, so isoleucine is not a competitive inhibitor. Also, the site to which isoleucine binds to the enzyme is different from the enzyme active site that binds to threonine. This second site, called the allosteric site, specifically recognizes isoleucine, whose presence there induces a change in the conformation of the enzyme such that threonine binds poorly to the active site. Thus, isoleucine exerts an inhibiting effect on the enzyme activity. As a result, the reaction slows as the concentration of isoleucine increases, and no excess isoleucine is produced. When the concentration of isoleucine falls to a low enough level, the enzyme becomes more active, and more isoleucine is synthesized. This type of allosteric regulation in which the enzyme that catalyzes the first step of a series of reactions is inhibited by the final product is called **feedback inhibition.** The control of enzyme activity by allosteric regulation of key enzymes is of immense benefit to an organism because it allows the concentration of cellular products to be maintained within very narrow limits.

modulator A substance that binds to an enzyme at a location other than the active site and alters the catalytic activity.

allosteric enzyme An enzyme with a quaternary structure whose activity is changed by the binding of modulators.

activator A substance that binds to an allosteric enzyme and increases its activity.

feedback inhibition A process in which the end product of a sequence of enzyme-catalyzed reactions inhibits an earlier step in the process.

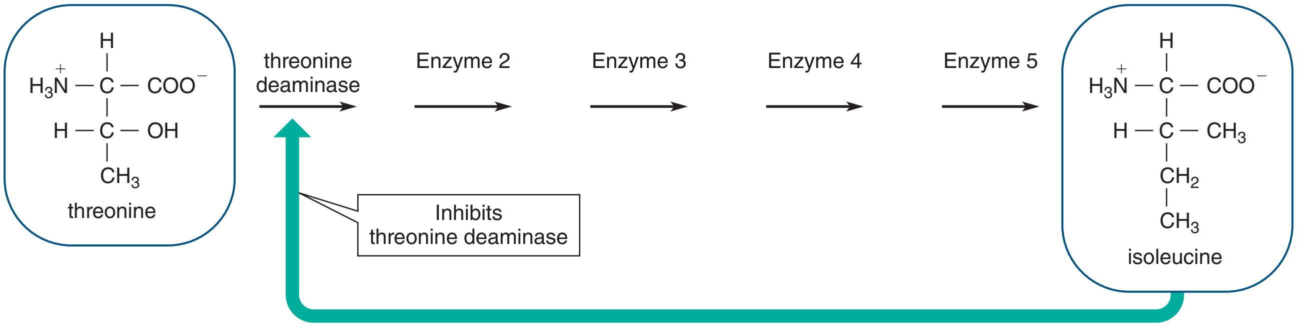


FIGURE 20.18 The allosteric regulation of threonine deaminase by isoleucine, an example of feedback inhibition.

20.8C Genetic Control

One way to increase production from an enzyme-catalyzed reaction, given a sufficient supply of substrate, is for a cell to increase the number of enzyme molecules present. The synthesis of all proteins, including enzymes, is under genetic control by nucleic acids (see **Chapter 21**). An example of the genetic control of enzyme activity involves **enzyme induction**, the synthesis of enzymes in response to a temporary need of the cell.

enzyme induction The synthesis of an enzyme in response to a cellular need.

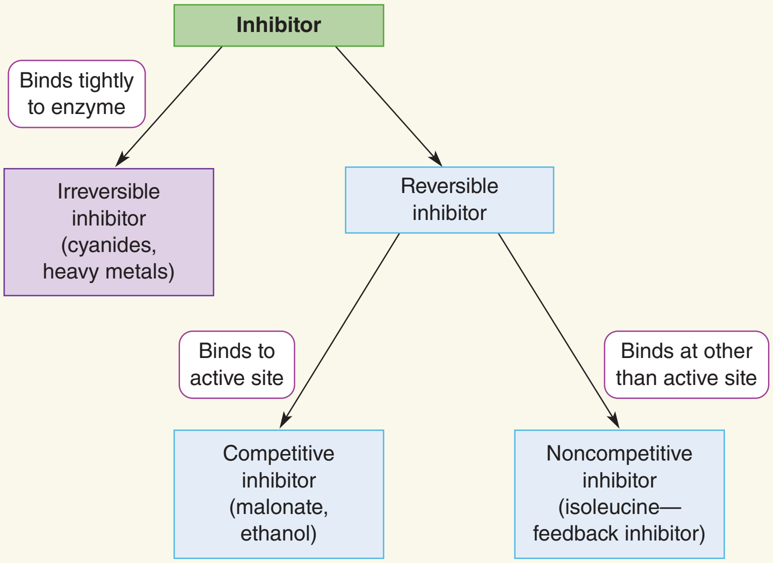
The first demonstrated example of enzyme induction came from studies conducted in the 1950s on the bacterium *Escherichia coli*. β-galactosidase, an enzyme required

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

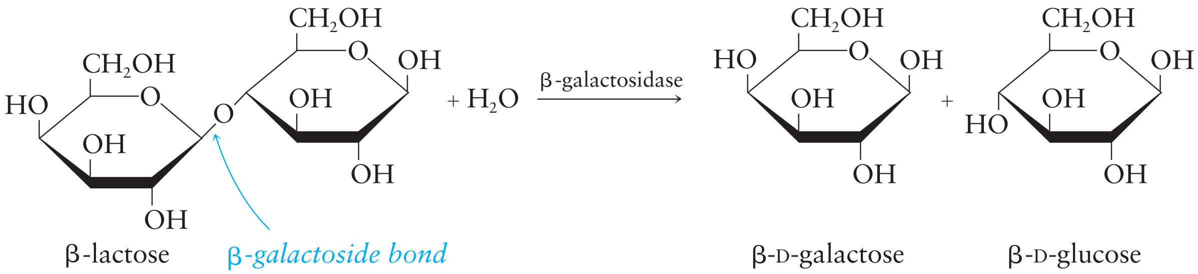
STUDY TOOLS 20.1

A Summary Chart of Enzyme Inhibitors

At this point in your study of enzymes, a summary chart is a useful tool for representing the various types of enzyme inhibitors in a compact, easy-to-review way.


Inhibitor
Binds tightly to enzyme
Irreversible inhibitor (cyanides, heavy metals)
Reversible inhibitor
Binds to active site
Binds at other than active site
Competitive inhibitor (malonate, ethanol)
Noncompetitive inhibitor (isoleucine—feedback inhibitor)

for the utilization of lactose, catalyzes the hydrolysis of lactose to D-galactose and D-glucose.


CH$_2$OH
HO
O
OH
OH
O
CH$_2$OH
O
OH
OH
OH
+ H$_2$O
β-galactosidase
HO
CH$_2$OH
O
OH
OH
OH
+
CH$_2$OH
O
OH
HO
OH
OH
β-lactose
β-galactoside bond
β-D-galactose
β-D-glucose

In the absence of lactose in the growth medium, there were fewer than 10 β-galactosidase molecules per cell of *E. coli*. However, if *E. coli* is added to a lactose-containing medium, within minutes the bacterium begins to produce thousands of molecules of β-galactosidase. This is an example of enzyme induction. If lactose is removed from the growth medium, the production of β-galactosidase again falls back to a low level.

The biological significance of the genetic control of enzyme activity is that it allows an organism to adapt to environmental changes. The coupling of genetic control and allosteric regulation of enzyme activity puts the cellular processes in the body under constant control.

Example 20.5 Describing Enzyme Control

List the three methods of cellular control over enzyme activity.

Solution

Activation of zymogens, allosteric regulation, and genetic control

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

✔ **LEARNING CHECK 20.5** Explain how each of the following processes is involved in the regulation of enzyme activity:

a. Activation of zymogens
b. Allosteric regulation
c. Genetic control

20.9 Medical Application of Enzymes

Learning Objective 9 Discuss the importance of measuring enzyme levels in the diagnosis of disease.

20.9A Enzymes in Clinical Diagnosis

Certain enzymes are normally found almost exclusively inside tissue cells and are released into the blood and other biological fluids only when these cells are damaged or destroyed. Because of the normal breakdown and replacement of tissue cells that go on constantly, the blood serum contains these enzymes but at very low concentrations—often a million times lower than the concentration inside cells. However, blood serum levels of cellular enzymes increase significantly when excessive cell injury or destruction occurs or when cells grow rapidly as a result of cancer. Changes in blood serum concentrations of specific enzymes can be used clinically to detect cell damage or uncontrolled growth, and even to suggest the site of the damage or cancer. Also, the extent of cell damage can often be estimated by the magnitude of the serum concentration increase above normal levels. For these reasons, the measurement of enzyme concentrations in blood serum and other biological fluids has become a major diagnostic tool, particularly in diagnosing diseases of the heart (see **Figure 20.19**), liver, pancreas, prostate, and bones. In fact, certain enzyme determinations are performed so often that they have become routine procedures in the clinical chemistry laboratory. **Table 20.7** lists some enzymes used in medical diagnosis.

iStock.com/kupicoo

FIGURE 20.19 Enzyme assays are extremely important in the diagnosis of heart attacks.

TABLE 20.7 Diagnostically Useful Assays of Blood Serum Enzymes

Enzyme	Pathological Condition
Acid phosphatase	Prostate cancer
Alanine transaminase (ALT)	Hepatitis
Alkaline phosphatase (ALP)	Liver or bone disease
Amylase	Diseases of the pancreas
Aspartate transaminase (AST)	Heart attack or hepatitis
Creatine kinase (CK)	Heart attack
Lactate dehydrogenase (LDH)	Heart attack, liver damage
Lipase	Acute pancreatitis
Lysozyme	Monocytic leukemia

20.9B Isoenzymes

Lactate dehydrogenase (LDH) and creatine kinase (CK), two of the enzymes listed in **Table 20.7**, are particularly useful in clinical diagnosis because each occurs in multiple forms called **isoenzymes**. Although all forms of a particular isoenzyme catalyze the same reaction, their molecular structures are slightly different and their locations within the body tissues may vary.

isoenzyme A slightly different form of the same enzyme produced by different tissues.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Probably the most fully studied group of isoenzymes is that of lactate dehydrogenase (LDH). The quaternary structure of the enzyme consists of four subunits that are of two different types. One is labeled H because it is the predominant subunit present in the LDH enzyme found in heart muscle cells. The other, labeled M, predominates in other muscle cells. There are five possible ways to combine these four subunits to form the enzyme (see **Figure 20.20**). Each combination has slightly different properties, which allows them to be separated and identified by electrophoresis.

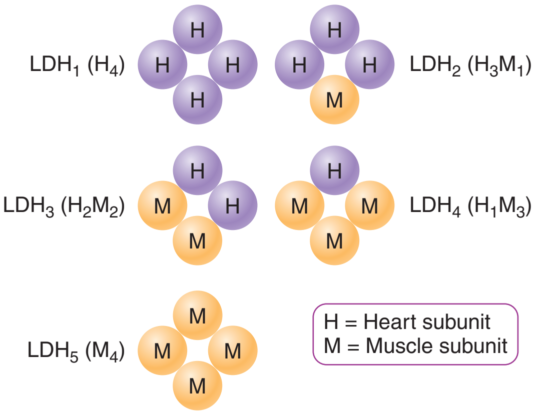


FIGURE 20.20 Isomeric forms (isoenzymes) of lactate dehydrogenase.

Table 20.8 shows the distribution of the five LDH isoenzymes in several human tissues. Notice that each type of tissue has a distinct pattern of isoenzyme percentages. Liver and skeletal muscle, for example, contain particularly high percentages of LDH_5. Also notice the differences in LDH_1 and LDH_2 levels in heart and skeletal muscles.

TABLE 20.8 Tissue Distribution of LDH Isoenzymes

Tissue	LDH_1 (%)	LDH_2 (%)	LDH_3 (%)	LDH_4 (%)	LDH_5 (%)
Brain	23	34	30	10	3
Heart	50	36	9	3	2
Kidney	28	34	21	11	6
Liver	4	6	17	16	57
Lung	10	20	30	25	15
Serum	28	41	19	7	5
Skeletal muscle	5	5	10	22	58

Because of the difference in tissue distribution of LDH isoenzymes, serum levels of LDH are used in the diagnosis of a wide range of diseases: anemias involving the rupture of red blood cells, acute liver diseases, congestive heart failure, and muscular diseases such as muscular dystrophy. This wide range of diseases makes an LDH assay a good initial diagnostic test. Elevated levels of LDH_1 and LDH_2, for example, indicate myocardial infarction, whereas elevated LDH_5 indicates possible liver damage. If LDH activity is elevated, then this and other isoenzyme assays can be used to pinpoint the location and type of disease more accurately.

Health Career Description

REGISTERED NURSE

Registered nurses may practice at an associate degree (ADN) or a bachelor's degree (BSN) level. Registered nurses are registered at the state level, and must pass a national exam called the NCLEX-RN. Once licensed in one state, it is relatively easy to become licensed in another state, as most states recognize the licensing procedures of other states.

It is very important however, to make sure you choose a nationally accredited and state recognized nursing program. Nonaccredited for-profit organizations offering nursing degrees can put graduates in situations where they may not be allowed to take the state board exam. So choose your school carefully. State universities are usually a safe bet. If you are unsure of a school's credentials, check with the board of nursing licensure for your state.

According to the Bureau of Labor Statistics, "Registered nurses (RNs) provide and coordinate patient care and educate patients and the public about various health conditions. Registered nurses work in hospitals, physicians' offices, home healthcare services, and nursing care facilities. Others work in outpatient clinics and schools."

Nursing skills include, but are not limited to, placing and maintaining IVs, administering medications, moving and positioning patients, ensuring patient comfort, logging medications and treatments in software programs, liaising between health care professionals, patients, and their families, providing lifesaving emergency treatments such as CPR, and providing end-of life support. Nurses may also educate patients and the public about health care policies and practices.

Practically every American will interact with a nurse at some time in their life. Nurses are trusted figures in society in much the same way as doctors or law-enforcement officials. We rely on nurses to keep health care running smoothly and to provide a bridge between doctor and patient. Nurses are expected to exhibit a certain level of selflessness and to serve the common good. This may result in the necessity of working nights, weekends, holidays, or during health crises. Nurses provide a strong component to the fabric of human society. Their contributions cannot be overestimated.

Sources: Medical News Today. (n.d.) What do Elevated Cardiac Enzymes Mean? Retrieved Apr. 26, 2020 from https://www.medicalnewstoday.com/articles/321684#what-do-elevated-cardiac-enzymes-mean National Institute of Health (NIH). (n.d.) Coronary Heart Disease. Retrieved Apr. 26, 2020 from https://www.nhlbi.nih.gov/health-topics/coronary-heart-disease NursingLicensure.org. (n.d.) How to Become an RN. Retrieved Apr. 26, 2020 from https://www.nursinglicensure.org/articles/how-to-become-an-rn.html

Concept Summary

20.1 General Characteristics of Enzymes

Learning Objective: Can you describe the general characteristics of enzymes and explain why enzymes are vital in body chemistry?

- Enzymes are highly efficient protein catalysts involved in almost every biological reaction.
- They are often quite specific in terms of the substance acted on and the type of reaction catalyzed.

20.2 Enzyme Nomenclature and Classification

Learning Objective: Can you determine the function and/or substrate of an enzyme on the basis of its name?

- Enzymes are grouped into six major classes on the basis of the type of reaction catalyzed.
- Common names for enzymes often end in *-ase*.
- Endings are based on the substrate and/or the type of reaction catalyzed.

20.3 Enzyme Cofactors

Learning Objective: Can you identify the general function of cofactors?

- Cofactors are nonprotein molecules required for an enzyme to be active.
- Cofactors are either organic (coenzymes) or inorganic ions.

20.4 The Mechanism of Enzyme Action

Learning Objective: Can you use the lock-and-key theory to explain specificity in enzyme action?

- The behavior of enzymes is explained by a theory in which the formation of an enzyme–substrate complex is assumed to occur.
- The specificity of enzymes is explained by the lock-and-key theory and the induced-fit theory.

20.5 Enzyme Activity

Learning Objective: Can you list two ways of describing enzyme activity?

- The catalytic ability of enzymes is described by turnover number and enzyme international units.
- Experiments that measure enzyme activity are referred to as enzyme assays.

20.6 Factors Affecting Enzyme Activity

Learning Objective: Can you identify the factors that affect enzyme activity?

- The catalytic activity of enzymes is influenced by numerous factors.
- The most important are substrate concentration, enzyme concentration, temperature, and pH.

20.7 Enzyme Inhibition

Learning Objective: Can you compare the mechanisms of competitive and noncompetitive enzyme inhibition?

- Chemical substances called inhibitors decrease the rates of enzyme-catalyzed reactions.
- Irreversible inhibitors render enzymes permanently inactive and include several very toxic substances, such as the cyanide ion and heavy-metal ions.
- Reversible inhibitors are of two types: competitive and noncompetitive.

20.8 The Regulation of Enzyme Activity

Learning Objective: Can you describe the three methods of cellular control over enzyme activity?

- Three mechanisms of cellular control over enzyme activity exist.
- One method involves the synthesis of enzyme precursors called zymogens, which are activated when needed by the cell.
- The second mechanism relies on the binding of small molecules (modulators), which increase or decrease enzyme activity.
- Genetic control of enzyme synthesis, the third method, regulates the amount of enzyme available.

20.9 Medical Application of Enzymes

Learning Objective: Can you discuss the importance of measuring enzyme levels in the diagnosis of disease?

- Numerous enzymes have become useful as aids in diagnostic medicine.
- The presence of specific enzymes in body fluids, such as blood, has been related to certain pathological conditions.

Key Terms and Concepts

Absolute specificity (20.1)
Activator (20.8)
Active site (20.4)
Allosteric enzyme (20.8)
Antibiotic (20.7)
Apoenzyme (20.3)
Coenzyme (20.3)
Cofactor (20.3)
Competitive inhibitor (20.7)
Enzyme (20.1)
Enzyme activity (20.5)
Enzyme induction (20.8)
Enzyme inhibitor (20.7)
Enzyme international unit (IU) (20.5)
Feedback inhibition (20.8)
Induced-fit theory (20.4)
Isoenzyme (20.9)
Lock-and-key theory (20.4)
Modulator (20.8)
Noncompetitive inhibitor (20.7)
Optimum pH (20.6)
Optimum temperature (20.6)
Relative specificity (20.1)
Stereochemical specificity (20.1)
Substrate (20.2)
Turnover number (20.5)
Zymogen or proenzyme (20.8)

Key Equations

1. Formation of an active enzyme (**Section 20.3**):	apoenzyme + cofactor (coenzyme or inorganic ion) → active enzyme	Reaction 20.4
2. Mechanism of enzyme action (**Section 20.4**):	$E + S \rightleftarrows ES \rightarrow E + P$	Reaction 20.6

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging

General Characteristics of Enzymes (Section 20.1)

20.1 What is the role of enzymes in the body?

20.2 List two ways that enzyme catalysis of a reaction is superior to normal laboratory conditions.

20.3 What is the relationship between an enzyme and the energy of activation for a reaction?

20.4 Why are so many different enzymes needed?

20.5 Define what is meant by the term *enzyme specificity.*

20.6 Define what is meant by the term *absolute specificity.*

20.7 List three ways in which enzymes are particularly well-suited for their essential roles in living organisms.

Enzyme Nomenclature and Classification (Section 20.2)

20.8 What name is given to the nomenclature system for enzymes?

20.9 What is the relationship between urea and urease? Between maltose and maltase?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

20.10 Identify which of the following are enzymes:

- **a.** Lactase
- **b.** Fructose
- **c.** Pyruvate
- **d.** Ethanol dehydrogenase

20.11 Identify which of the following are enzymes:

- **a.** Galactose
- **b.** Cellulase
- **c.** Tryptophan synthetase
- **d.** Catalase

20.12 Refer to **Table 20.1**. Identify the six EC classifications to which each of the following enzymes belongs, based on the reactions they catalyze:

- **a.** Hydrolyzes ether linkages
- **b.** Transfers –OH groups between molecules
- **c.** Dehydrates alcohols forming carbon–carbon double bonds
- **d.** Uses ATP to join two molecules

20.13 Refer to **Table 20.1**. Identify the six EC classifications to which each of the following enzymes belongs, based on the reactions they catalyze:

- **a.** Converts an L isomer to a D-isomer
- **b.** Oxidizes nitrite
- **c.** Hydrolyzes glycosidic linkages
- **d.** Transfers amine groups from urea to other molecules

20.14 Match the following enzymes and substrates:

Enzyme	Substrate
a. Sucrase	maltose
b. Amylase	amylose
c. Lactase	sucrose
d. Maltase	arginine
e. Arginase	lactose

20.15 Match the following enzymes and substrates:

Enzyme	Substrate
a. Chitinase	peroxides
b. Hyaluronidase	urea
c. Peroxidase	chitin
d. Cellulase	hyaluronic acid
e. Urease	cellulose

20.16 Match the following general enzyme names and reactions catalyzed:

Enzyme	Reaction Catalyzed
a. Decarboxylase	formation of ester linkages
b. Phosphatase	removal of carboxyl groups from compounds
c. Peptidase	hydrolysis of peptide linkages
d. Esterase	hydrolysis of phosphate ester linkages

20.17 Match the following general enzyme names and reactions catalyzed:

Enzyme	Reaction Catalyzed
a. Dehydrolase	adds oxygen to molecules
b. Dehydrogenase	adds carboxyl groups to molecules
c. Oxygenase	removes water molecules
d. Carboxylase	removes hydrogens from molecules

20.18 Because one substrate may undergo a number of reactions, it is often convenient to use an enzyme nomenclature system that includes both the substrate name (or general type) and the type of reaction catalyzed. Identify the substrate and type of reaction for the following enzyme names:

- **a.** succinate dehydrogenase
- **b.** L-amino acid reductase
- **c.** cytochrome oxidase
- **d.** glucose-6-phosphate isomerase

20.19 Because one substrate may undergo a number of reactions, it is often convenient to use an enzyme nomenclature system that includes both the substrate name (or general type) and the type of reaction catalyzed. Identify the substrate and type of reaction for the following enzyme names:

- **a.** Pyruvate carboxylase
- **b.** Alcohol dehydrogenase
- **c.** Glutamate deaminase
- **d.** Amino acid transferase

20.20 Give a two-word name (substrate + reaction type) for an enzyme that catalyzes each of the following reactions:

- **a.** Oxidation of nitrite
- **b.** Isomerization of fructose
- **c.** Removal of hydrogen from lactate
- **d.** Hydrolysis of lactose

20.21 Give a two-word name (substrate + reaction type) for an enzyme that catalyzes each of the following reactions:

- **a.** Reduction of oxalate
- **b.** Decarboxylation of citrate
- **c.** Removes an amine group from adenosine
- **d.** Forms an ether linkage between two alcohol molecules

20.22 Classify each of the following as a simple or a conjugated enzyme.

- **a.** Has both a protein and a nonprotein part
- **b.** Requires a Zn^{2+} ion for activity
- **c.** Has only amino acids in it
- **d.** Contains a cofactor

20.23 Classify each of the following as a simple or a conjugated enzyme.

- **a.** Contains a carbohydrate part
- **b.** Contains only protein
- **c.** Has a vitamin as part of its structure
- **d.** Requires a Cl^{-} ion for activity

Enzyme Cofactors (Section 20.3)

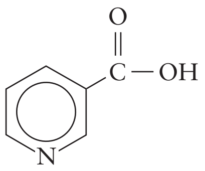
20.24 Some enzymes consist of protein plus another component. Which of the terms *cofactor* or *coenzyme* correctly describes each of the following nonprotein components?

a. an inorganic ion

b. a nonspecific component

c. an organic material

d. nicotinic acid,



20.25 Some enzymes consist of protein plus another component. Which of the terms *cofactor* or *coenzyme* correctly describes each of the following nonprotein components?

a. Vitamin B_6

b. NAD^+

c. An undescribed component

d. Mg^{2+} ion

20.26 What are the relationships among the terms *cofactor*, *active enzyme*, and *apoenzyme*?

20.27 State the relationship between vitamins and enzyme activity.

20.28 List some typical inorganic ions that serve as cofactors.

20.29 What vitamins are required for FAD and NAD^+ formation?

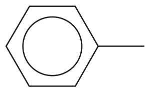
The Mechanism of Enzyme Action (Section 20.4)

20.30 Explain what is meant by the following equation:

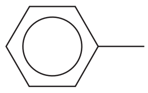
$$E + S \rightleftarrows ES \rightarrow E + P$$

20.31 In what way are the substrate and active site of an enzyme related?

20.32 Match the following substrates with the groups found in different enzyme active sites that would allow an enzyme–substrate complex to form.

Substrate	Enzyme Active Site
a. $^{-}OOC—CH_2—OH$	Fe^{2+}
b. $CH_3CH_2—COO^-$	
c. $CH_3CH_2CH_2CH_2CH_3$	HO-

20.33 Match the following substrates with the groups found in different enzyme active sites that would allow an enzyme-substrate complex to form.

Substrate	Enzyme Active Site
a. $^{-}OOC—CH_2—NH_3^+$	
b. $CH_3CH_2—NH_2$	$–COO^-$
c. $CH_3CH═CHCH_3$	HO–

20.34 Explain why the forces that hold a substrate in an enzyme active site are not covalent bonds.

20.35 How is enzyme specificity explained by the lock-and-key theory?

20.36 Compare the lock-and-key theory with the induced-fit theory.

20.37 An enzyme can catalyze reactions involving propanoic acid, butanoic acid, and pentanoic acid. Would the lock-and-key theory or the induced-fit theory best explain this enzyme's mechanism of action? Why?

Enzyme Activity (Section 20.5)

20.38 List two ways of describing enzyme activity.

20.39 What observations may be used in experiments to determine enzyme activity?

20.40 Define the term *turnover number.*

20.41 What is an enzyme international unit? Why is the international unit a useful method of expressing enzyme activity in medical diagnoses?

20.42 The turnover number for cholinesterase is 1.5×10^6 acetylcholine molecules per minute. How many acetylcholine molecules could be hydrolyzed in one hour by one cholinesterase enzyme molecule?

20.43 What is the turnover number in molecules/min of a catalase enzyme molecule that cleaves 8.4×10^7 H_2O_2 molecules in 15 minutes?

20.44 One micromole (mcmol) of substrate is 6.0×10^{17} molecules of substrate. Carbonic anhydrase has a turnover number of 3.6×10^7 substrate molecules per minute. How many carbonic anhydrase enzyme molecules are in one international unit?

Factors Affecting Enzyme Activity (Section 20.6)

20.45 Use graphs to illustrate enzyme activity as a function of the following:

a. substrate concentration

b. enzyme concentration

c. pH

d. temperature

20.46 Write a single sentence to summarize the information of each graph in Exercise 20.27.

20.47 What happens to the rate of an enzyme-catalyzed reaction as substrate concentration is raised beyond the saturation point?

20.48* How might V_{max} for an enzyme be determined?

20.49 How would you expect hypothermia to affect enzyme activity in the body?

20.50 A lab tech is determining the V_{max} for an enzyme by periodically adding more substrate to the assay over time. Instead of adding substrate to the assay, one time he mistakenly added enzyme. Explain what will happen to the V_{max} value.

20.51 Explain why temperature can affect enzyme reaction rates in two ways: an increase in temperature can increase the rate of the reaction, or it can slow down and stop the reaction.

20.52 Explain why all enzymes do not have the same optimum pH.

20.53 When handling or storing solutions of enzymes, the pH is usually kept near 7.0. Explain why.

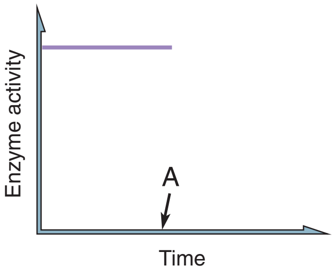
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Enzyme Inhibition (Section 20.7)

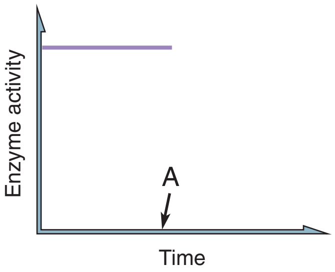
20.54 Distinguish between irreversible and reversible enzyme inhibition.

20.55 Distinguish between competitive and noncompetitive enzyme inhibition.

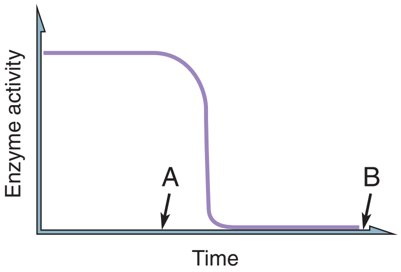
20.56 Complete the graph below, illustrating what would happen to enzyme activity if excess Hg^{2+} ions were added at point "A" and "poisoned" the enzyme molecules.



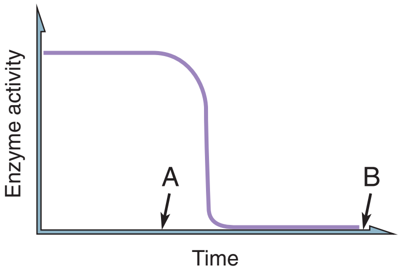
20.57 Complete the graph below, illustrating what would happen to enzyme activity if insufficient Hg^{2+} ions were added at point "A" to "poison" all the enzyme molecules.



20.58 An enzyme assay had a competitive inhibitor added to it at point "A" on the graph below. Complete the graph, illustrating what would happen to enzyme activity if more substrate were added at point "B."



20.59 An enzyme assay had a noncompetitive inhibitor mixture added to it at point "A" on the graph below. Complete the graph, illustrating what would happen to enzyme activity if more substrate were added at point "B."



20.60 Determine what type(s) of enzyme inhibitor(s) each of the following statement characterizes. Choices are: irreversible, reversible-competitive, reversible-non-competitive, or more than one of these (list which ones).

- **a.** Enzyme active site can be occupied by substrate or inhibitor, but not both.
- **b.** Adding more substrate does not reverse the inhibitor effect
- **c.** Substrate and inhibitor structure do not have to resemble each other
- **d.** Substrate and inhibitor can bind to the enzyme at the same time.

20.61 Determine what type(s) of enzyme inhibitor(s) each of the following statement characterizes. Choices are: irreversible, reversible-competitive, reversible-non-competitive, or more than one of these (list which ones).

- **a.** Adding more substrate reverses inhibitor effect
- **b.** Substrate and inhibitor structure resemble each other
- **c.** Substrate and inhibitor cannot bind to the enzyme at the same time
- **d.** May cause enzyme denaturation

20.62 How does each of the following irreversible inhibitors interact with enzymes?

- **a.** cyanide
- **b.** heavy-metal ions

20.63 List an antidote for each of the two poisons in Exercise 20.62 and describe how each functions.

The Regulation of Enzyme Activity (Section 20.8)

20.64 Why is the regulation of enzyme activity necessary?

20.65 List three mechanisms for the control of enzyme activity.

20.66 Describe the importance of zymogens in the body. Give an example of an enzyme that has a zymogen.

20.67* The clotting of blood occurs by a series of zymogen activations. Why are the enzymes that catalyze blood clotting produced as zymogens?

20.68 Describe the process by which most zymogens are activated where they are needed.

20.69 What type of enzyme possesses a binding site for modulators?

20.70 Name and contrast the two types of modulators.

20.71 Explain why modulators must bind to an enzyme in a place other than the enzyme's active site.

20.72* Explain how feedback enzyme inhibition works and why it is advantageous for the cell.

20.73 What is meant by genetic control of enzyme activity and enzyme induction?

Medical Application of Enzymes (Section 20.9)

20.74 Why are enzyme assays of blood serum useful in a clinical diagnosis?

Even-numbered exercises answered in Appendix B.
Exercises with an asterisk (*) are more challenging.

20.75 How is each of the following enzyme assays useful in diagnostic medicine?

- **a.** CK
- **b.** ALP
- **c.** amylase

20.76 How is each of the following enzyme assays useful in diagnostic medicine?

- **a.** Acid phosphatase
- **b.** Lipase
- **c.** AST

20.77 What are isoenzymes? List two examples of isoenzymes.

20.78 Why is an LDH assay a good initial diagnostic test?

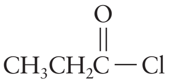
20.79 What specific enzyme assays are particularly useful in diagnosing liver damage or disease?

Additional Exercises

20.80 Carboxypeptidase is a proteolytic enzyme that cleaves the C-terminal amino acid residue from a polypeptide. The amino acid arginine is found in the active site of carboxypeptidase and is responsible for holding the C-terminal end of the polypeptide in place so the cleavage of the peptide bond can occur. What type of interaction occurs between the C-terminal end of the polypeptide and the arginine side chain?

20.81 An enzyme preparation that decarboxylates butanoic acid has an activity of 50 IU. How many grams of butanoic acid will this enzyme preparation decarboxylate in 10 minutes? Assume an unlimited supply of substrate.

20.82 Propanoic acid chloride was found to react with the side chain of a serine residue on an enzyme to cause irreversible inhibition of that enzyme. Suggest a mechanism of how this occurs.



$$CH_3CH_2\overset{\overset{\displaystyle O}{\|}}{C}-Cl$$

20.83 1.0×10^{12} enzyme molecules were added to 1.0 L of substrate solution with an initial pH of 7.0. After 1.0 minute, the solution had a pH of 6.0. Assume an unlimited supply of substrate and any change in hydrogen ion concentration was due to the following reaction.

$$\text{Substrate} \xrightarrow{\text{enzyme}} \text{Product} + H^+$$

- **a.** What was the change in H^+ concentration?
- **b.** How many molecules of substrate were reacted to cause this change in H^+ concentration?
- **c.** What is the turnover number of this enzyme?

20.84 The following reaction has come to equilibrium and it is found that there are 100 times as many molecules of A as there are of B in the solution.

$$A \rightleftharpoons B$$

An enzyme that catalyzes this reaction is then added to the solution. In which direction will the equilibrium shift?

Chemistry for Thought

20.85 Explain how the pasteurization of milk utilizes one of the factors that influence enzyme activity.

20.86 Explain how food preservation by freezing utilizes one of the factors that influence enzyme activity.

20.87 Some pottery glazes contain lead compounds. Why would it be unwise to use such pottery to store or serve food?

20.88 Urease can catalyze the hydrolysis of urea, but not the hydrolysis of methyl urea. Why?

20.89 The active ingredient in meat tenderizer is the enzyme papain, a protease. Explain how treating meat with this material before cooking would make it more tender.

20.90 Why are enzymes that are used for laboratory or clinical work stored in refrigerators?

20.91 Describe the differences between graphs showing temperature versus reaction rate for an enzyme-catalyzed reaction and an uncatalyzed reaction.

20.92 Answer the question associated with **Figure 20.3**. How else might ammonia be detected?

20.93 In **Figure 20.12**, it is noted that pickles resist spoilage. Why is that true for this acidic food?

20.94 One of the steps in preparing frozen corn for the grocery market involves "blanching" (briefly placing the corn in boiling water). Why is blanching necessary?

20.95 What experiment would you conduct to determine if an inhibitor is competitive or noncompetitive?

20.96 Why might an enzyme be selected over an inorganic catalyst for a certain industrial process?

20.97 Enzymes are enormous molecules, and yet the active site is relatively small. Why is a huge molecule necessary for enzymes?

21 Nucleic Acids and Protein Synthesis

Creaturart Images/Shutterstock.com

Environmental Career Focus

AVIAN FIELD TECHNICIAN

I got up at 3:00 a.m. to meet the duck hunters at dawn—but not to hunt. Today, we were capturing hundreds of ducks with a cannon net. It was a lot of fun! Everyone wore chest waders to untangle ducks from the nets in the lake. I set up the field lab with rows of cotton swabs, collection tubes, markers, and clipboards of instructions.

I work for a biological laboratory. This year, 20 hunters volunteered to help our principal investigator conduct bird flu tests. We collect swabs from ducks and analyze the samples for DNA mutations occurring in the virus from year to year.

Studying ducks is an important part of defending human populations against zoonotic viruses—viruses that originate in animals and then cross over to humans. This research provided a rare chance for hunters to interact with, and then release, the beautiful birds. I love the connection with nature and the importance of my work. What a wonderful day!

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Identify the components of nucleotides and correctly classify the sugars and bases. **(Section 21.1)**
2. Describe the structure of DNA. **(Section 21.2)**
3. Outline the process of DNA replication. **(Section 21.3)**
4. Contrast the structures of DNA and RNA and list the function of the three main types of cellular RNA. **(Section 21.4)**
5. Describe what is meant by the terms *transcription* and *translation*. **(Section 21.5)**
6. Describe the process by which RNA is synthesized in cells. **(Section 21.6)**
7. Explain how the genetic code functions in the flow of genetic information. **(Section 21.7)**
8. Outline the process by which proteins are synthesized in cells. **(Section 21.8)**
9. Describe how genetic mutations occur and how they influence organisms. **(Section 21.9)**
10. Describe the technology used to produce recombinant DNA. **(Section 21.10)**

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

ONE OF THE MOST remarkable properties of living cells is their ability to produce nearly exact replicas of themselves through hundreds of generations. Such a process requires that certain types of information be passed unchanged from one generation to the next. The transfer of necessary genetic information to new cells is accomplished by means of biomolecules called **nucleic acids**. The high molecular weight compounds represent coded information, much as words represent information in a book. It is the nearly infinite variety of possible structures that enables nucleic acids to represent the huge amount of information that must be transmitted sexually or asexually to reproduce a living organism. This information controls the inherited characteristics of the individuals in the new generation and determines the life processes as well (see **Figure 21.1**).

nucleic acid A biomolecule involved in the transfer of genetic information from existing cells to new cells.

© Michael C. Slabaugh

FIGURE 21.1 Nucleic acids passed from the parents to offspring determine the inherited characteristics.

21.1 Components of Nucleic Acids

Learning Objective 1 Identify the components of nucleotides and correctly classify the sugars and bases.

Nucleic acids are classified into two categories: **ribonucleic acid (RNA)**, found mainly in the cytoplasm of living cells, and **deoxyribonucleic acid (DNA)**, found primarily in the nuclei of cells. Both DNA and RNA are polymers, consisting of long, linear molecules. The repeating structural units, or monomers, of the nucleic acids are called **nucleotides**. Nucleotides, however, are composed of three simpler components: a heterocyclic base, a sugar, and a phosphate (see **Figure 21.2**). These components will be discussed individually.

ribonucleic acid (RNA) A nucleic acid found mainly in the cytoplasm of cells.

deoxyribonucleic acid (DNA) A nucleic acid found primarily in the nuclei of cells.

nucleotide The repeating structural unit or monomer of polymeric nucleic acids.

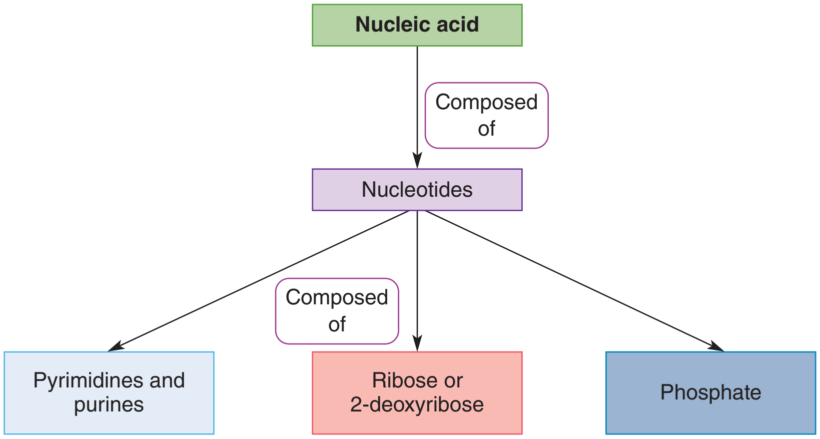
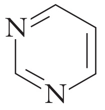
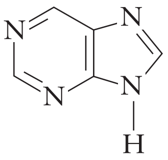


FIGURE 21.2 The composition of nucleic acids.

Each of the five bases commonly found in nucleic acids are heterocyclic compounds that can be classified as either a pyrimidine or a purine, the parent compounds from which the bases are derived:



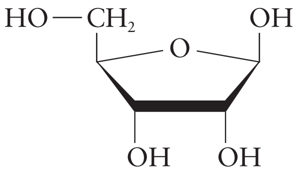
pyrimidine



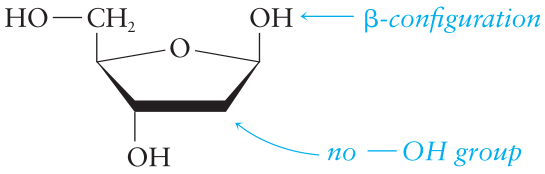
purine

The three pyrimidine bases are uracil, thymine, and cytosine, usually abbreviated U, T, and C. Adenine (A) and guanine (G) are the two purine bases. Adenine, guanine, and cytosine are found in both DNA and RNA, but uracil is ordinarily found only in RNA, and thymine only in DNA. Structural formulas of the five bases are given in **Figure 21.3**.

The sugar component of RNA is D-ribose, as the name ribonucleic acid implies. In deoxyribonucleic acid (DNA), the sugar is D-deoxyribose, as it lacks one oxygen atom at the second position of the heterocyclic ring. Both sugars occur in the β-configuration.

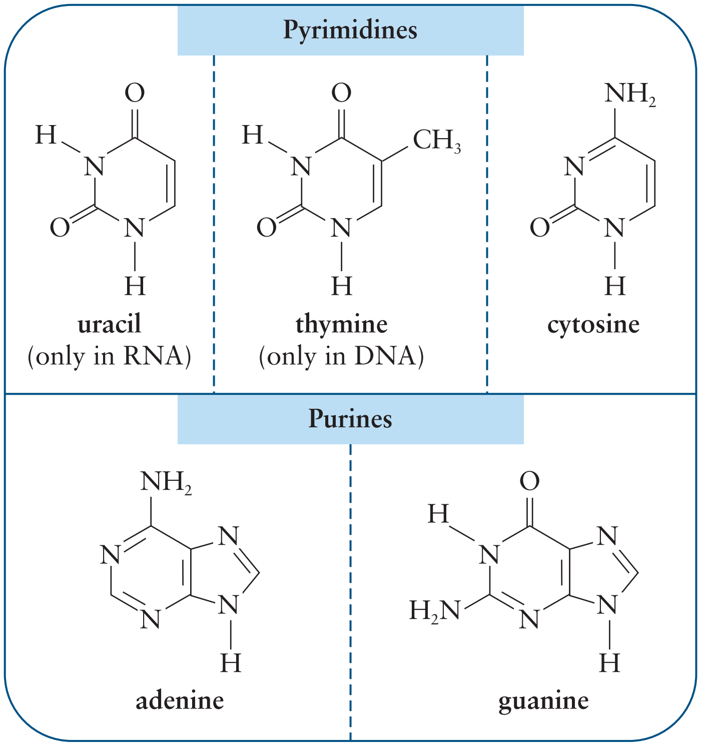


D-ribose

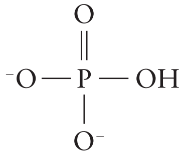


D-deoxyribose

FIGURE 21.3 The major bases of nucleic acids.



Phosphate, the third component of nucleotides, is derived from phosphoric acid (H_3PO_4), which under cellular pH conditions exists in ionic form:



$$^{-}O-\overset{\overset{\displaystyle O}{\|}}{\underset{\underset{\displaystyle O^{-}}{|}}{P}}-OH$$

Example 21.1 Identifying Bases

Indicate whether each of the following bases is a purine or a pyrimidine. Also, state whether it is found in DNA, RNA, or both.

a. cytosine
b. uracil
c. guanine

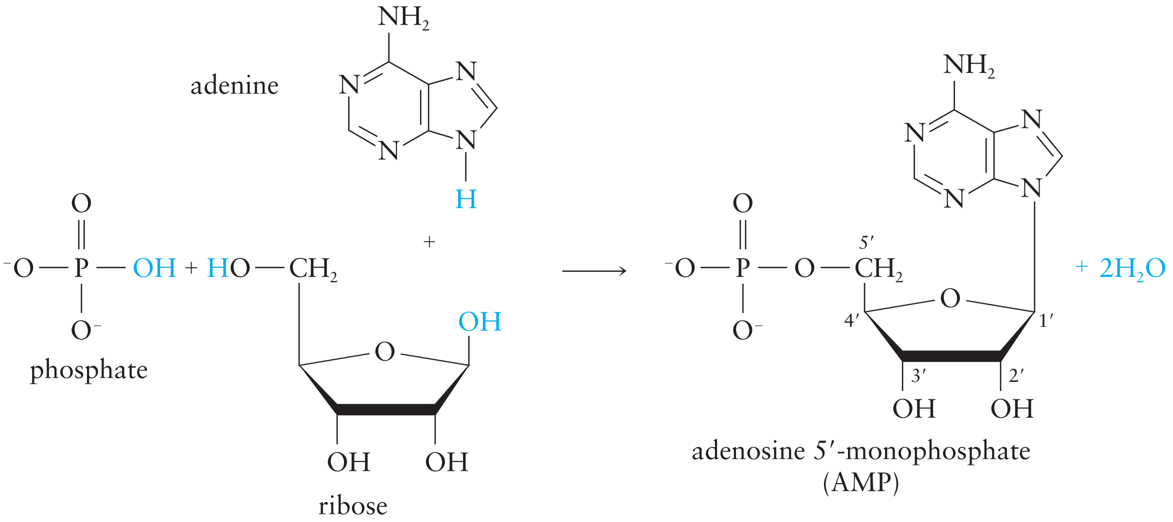
Solution

a. pyrimidine, both DNA and RNA
b. pyrimidine, RNA
c. purine, both DNA and RNA

✔ **LEARNING CHECK 21.1** Indicate whether each of the following bases is a purine or pyrimidine. Also, state whether it is found in DNA, RNA, or both.

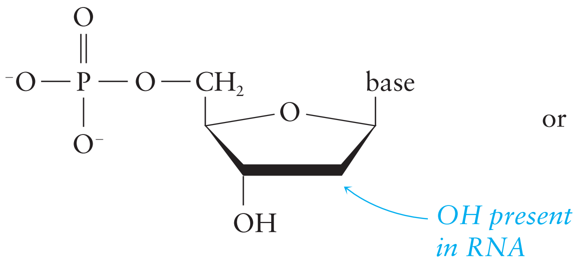
a. adenine
b. thymine

The formation of a nucleotide from these three components is represented in **Reaction 21.1**:

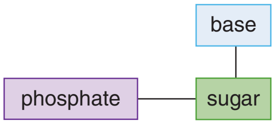

adenine
NH2
N
N
N
N
H
+
O
-O—P—OH + HO—CH2
O-
phosphate
OH
O
OH
OH
ribose
NH2
N
N
N
N
O
-O—P—O—CH2
O-
5′
4′
O
1′
3′
2′
OH
OH
+ 2H2O
adenosine 5′-monophosphate
(AMP)

(21.1)

In a nucleotide, the base is always attached to the 1′ position of the sugar, and the phosphate is generally located at the 5′ position. The carbon atoms in the sugar are designated with a number followed by a prime to distinguish them from the atoms in the bases. Because the nucleotide of **Reaction 21.1** contains ribose as the sugar, the nucleotide must be one found in RNA. The general structure of a nucleotide can be represented as

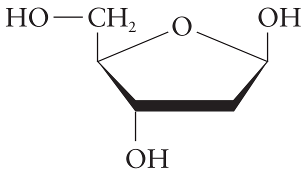

O
-O—P—O—CH2
O-
O
base
OH
OH present in RNA

or

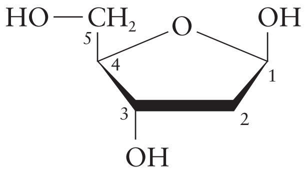

base
phosphate
sugar

Example 21.2 Numbering Sugar Positions

Number each of the carbon atoms in the deoxyribose structure below:



Solution



✓ LEARNING CHECK 21.2

a. In a nucleotide structure, a base is attached to which carbon position of a ribose or deoxyribose sugar?
b. What group is generally attached at the 5′ position in a nucleotide?

21.2 The Structure of DNA

Learning Objective 2 Describe the structure of DNA.

nucleic acid backbone The sugar–phosphate chain that is common to all nucleic acids.

DNA molecules, among the largest molecules known, contain between 1 million and 100 million nucleotide units. The nucleotides are joined together in nucleic acids by phosphate groups that connect the 5′ carbon of one nucleotide to the 3′ carbon of the next. These linkages are referred to as *phosphodiester bonds.* The result is a chain of alternating phosphate and sugar units to which the bases are attached. The sugar–phosphate chain is referred to as the **nucleic acid backbone**, and it is constant throughout the entire DNA molecule (see **Figure 21.4**). Thus, one DNA molecule differs from another only in the sequence, or order of attachment, of the bases along the backbone. Just as the amino acid sequence of a protein determines the primary structure of the protein, the order of the bases provides the primary structure of DNA.

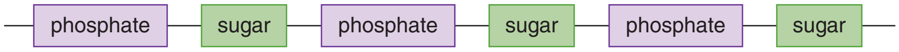


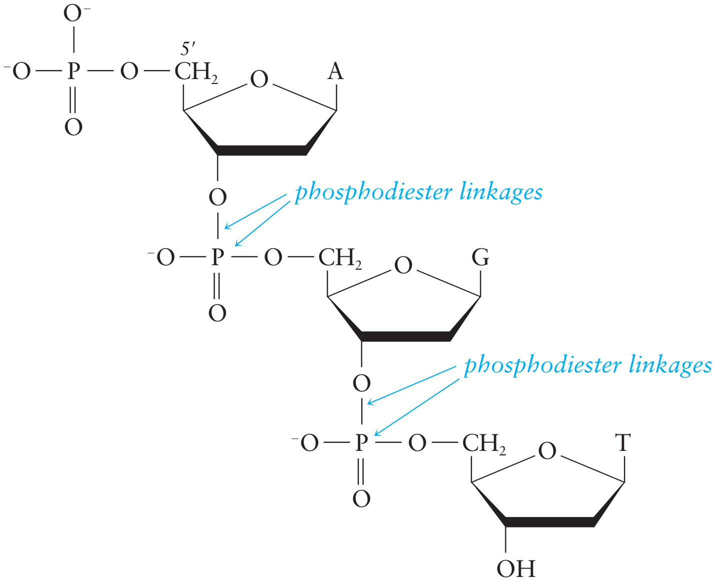
FIGURE 21.4 The nucleic acid backbone.

Figure 21.5 shows the structure of a tetranucleotide that represents a partial structural formula of a DNA molecule. The end of the polynucleotide segment of DNA in **Figure 21.5** that has no nucleotide attached to the 5′ CH_2 is called the 5′ end of the segment. The other end of the chain is the 3′ end. By convention, the sequence of bases along the backbone is read from the 5′ end to the 3′ end. Because the backbone structure along the chain does not vary, a polynucleotide structure may conveniently be abbreviated by giving only the sequence of the bases along the backbone. For example, ACGT represents the tetranucleotide in **Figure 21.5**.

Example 21.3 Drawing Trinucleotide Structures

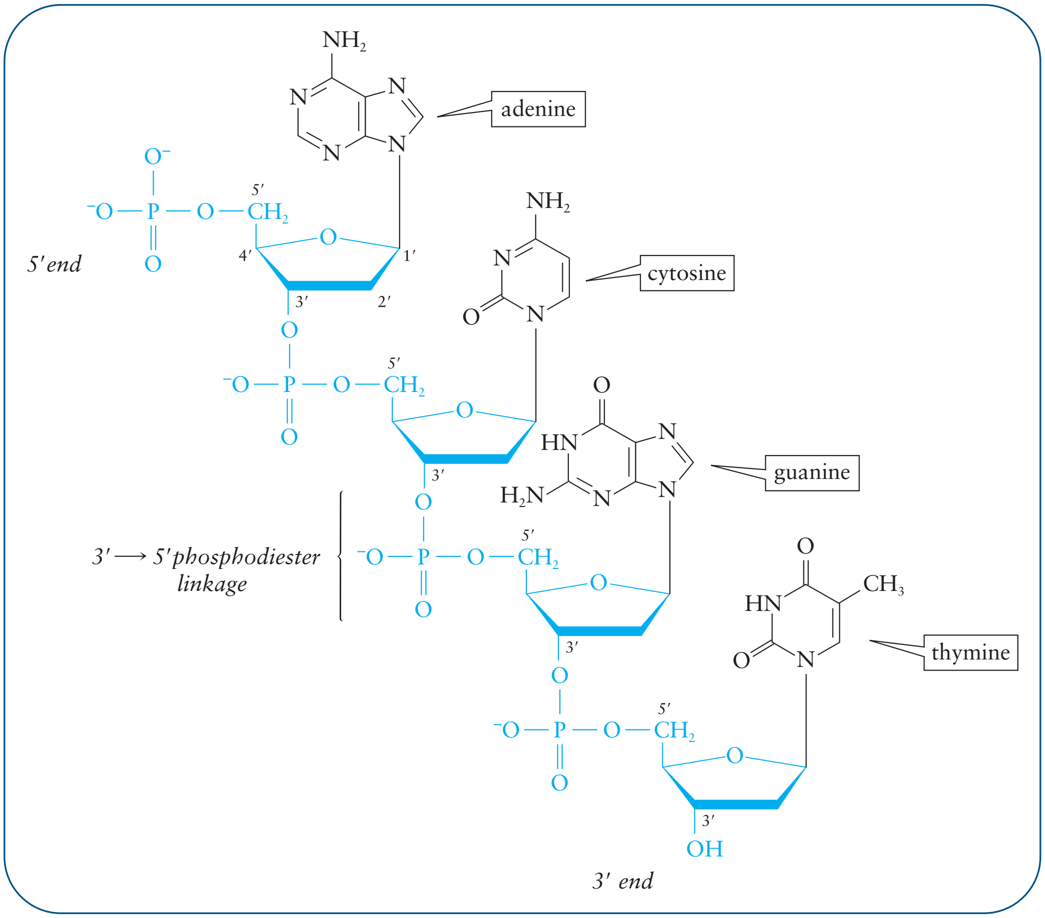
Draw the structural formula for a trinucleotide portion of DNA with the sequence AGT. Abbreviate the structures of the bases, using the letters AGT. Point out the 5′ and 3′ ends of the molecule. Indicate with arrows the phosphodiester linkages.

Solution



phosphodiester linkages
phosphodiester linkages
5′
A
G
T
OH

✔ **LEARNING CHECK 21.3** Draw the structural formula for a trinucleotide portion of DNA with the sequence CTG. Point out the 5′ and 3′ ends of the molecule. Indicate with arrows the phosphodiester linkages. Enclose the nucleotide corresponding to T in a box with dotted lines.



adenine
cytosine
guanine
thymine
5′end
3′ → 5′phosphodiester linkage
3′ end
5′
4′
1′
3′
2′

FIGURE 21.5 The structure of ACGT, a tetranucleotide segment of DNA. The nucleic acid backbone is in color.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

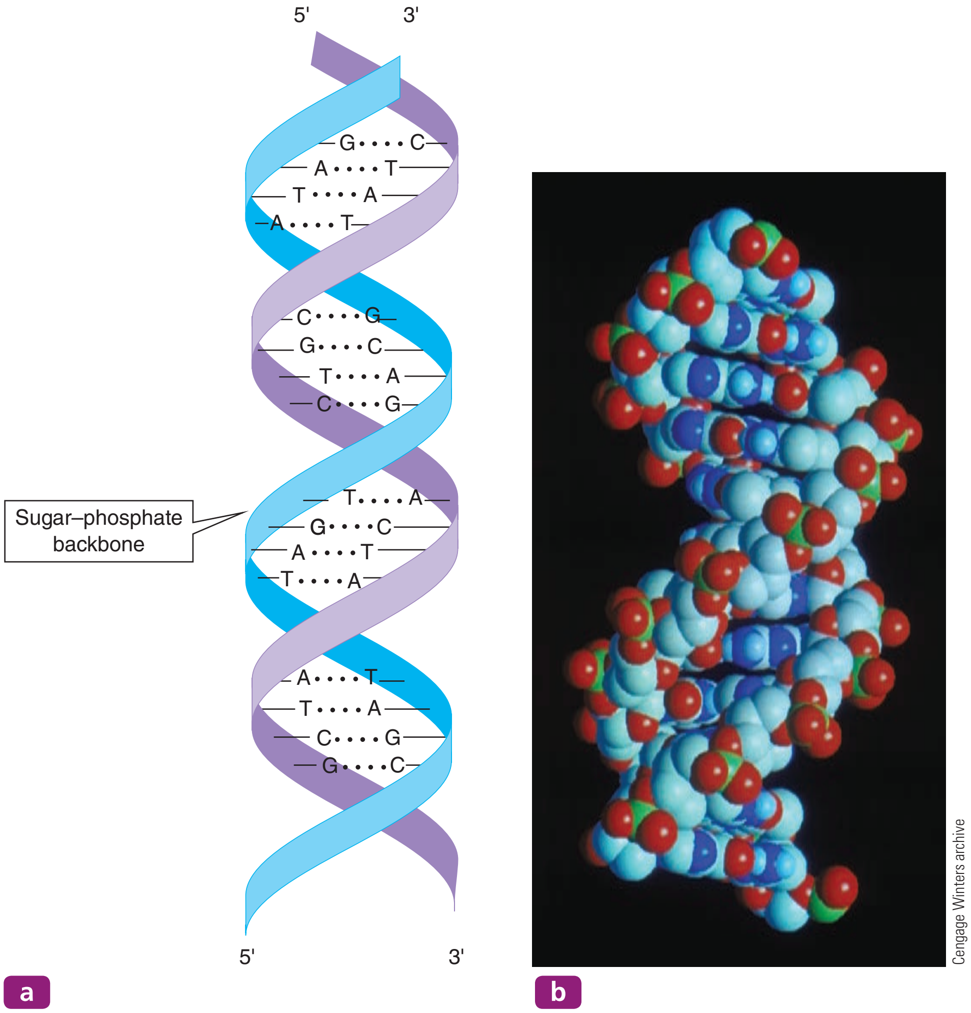
Pictorial Press Ltd/Alamy Stock Photo

FIGURE 21.6 Rosalind Franklin, a research scientist at Kings College London, provided the x-ray crystallography data that led to the discovery of the DNA double helix. Many believe that she should have been included in the 1962 Nobel Prize.

21.2A The Secondary Structure of DNA

The secondary structure of DNA was proposed in 1953 by American molecular biologist James D. Watson and English biologist Francis H. C. Crick. This was perhaps the greatest discovery of modern biology, and it earned its discoverers the Nobel Prize in Physiology or Medicine in 1962.

The model of DNA established by Watson and Crick was based on key contributions of other researchers (see **Figure 21.6**), including the analysis of the base composition of DNA. The analysis of DNA from many different forms of life revealed an interesting pattern. The relative amounts of each base often varied from one organism to another, but in all DNA the percentages of adenine and thymine were always equal to each other as were the percentages of guanine and cytosine. For example, human DNA contains 20% guanine, 20% cytosine, 30% adenine, and 30% thymine. Watson and Crick concluded from these and other types of data that DNA is composed of two strands entwined around each other in a double helix, as shown in **Figure 21.7**.



Cengage Winters archive

FIGURE 21.7 The double helix of DNA: (**a**) a schematic drawing and (**b**) a three-dimensional molecular model. Both representations show the bases pointing toward the center of the helix away from the sugar–phosphate backbone.

The two intertwined polynucleotide chains of the DNA double helix run in opposite (antiparallel) directions. Thus, each end of the double helix contains the 5′ end of one chain and the 3′ end of the other. The sugar–phosphate backbone is on the outside of the helix, and the bases point inward. The unique feature of the Watson and Crick structure is the way in which the chains are held together to form the double helix. They theorized that the DNA structure is stabilized by hydrogen bonding between the bases that extend inward

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

from the sugar–phosphate backbone (see **Figure 21.8**). The spacing in the interior of the double helix is such that adenine always hydrogen bonds to thymine, and guanine always hydrogen bonds to cytosine. Thus, in double-helical DNA, wherever there is an adenine on one strand of the helix, there must be a thymine on the other strand, and similarly for guanine and cytosine. The two DNA strands with these matched sequences are said to be **complementary** to each other.

complementary DNA strands Two strands of DNA in a double-helical form such that adenine and guanine of one strand are matched and hydrogen bonded to thymine and cytosine, respectively, of the second strand.

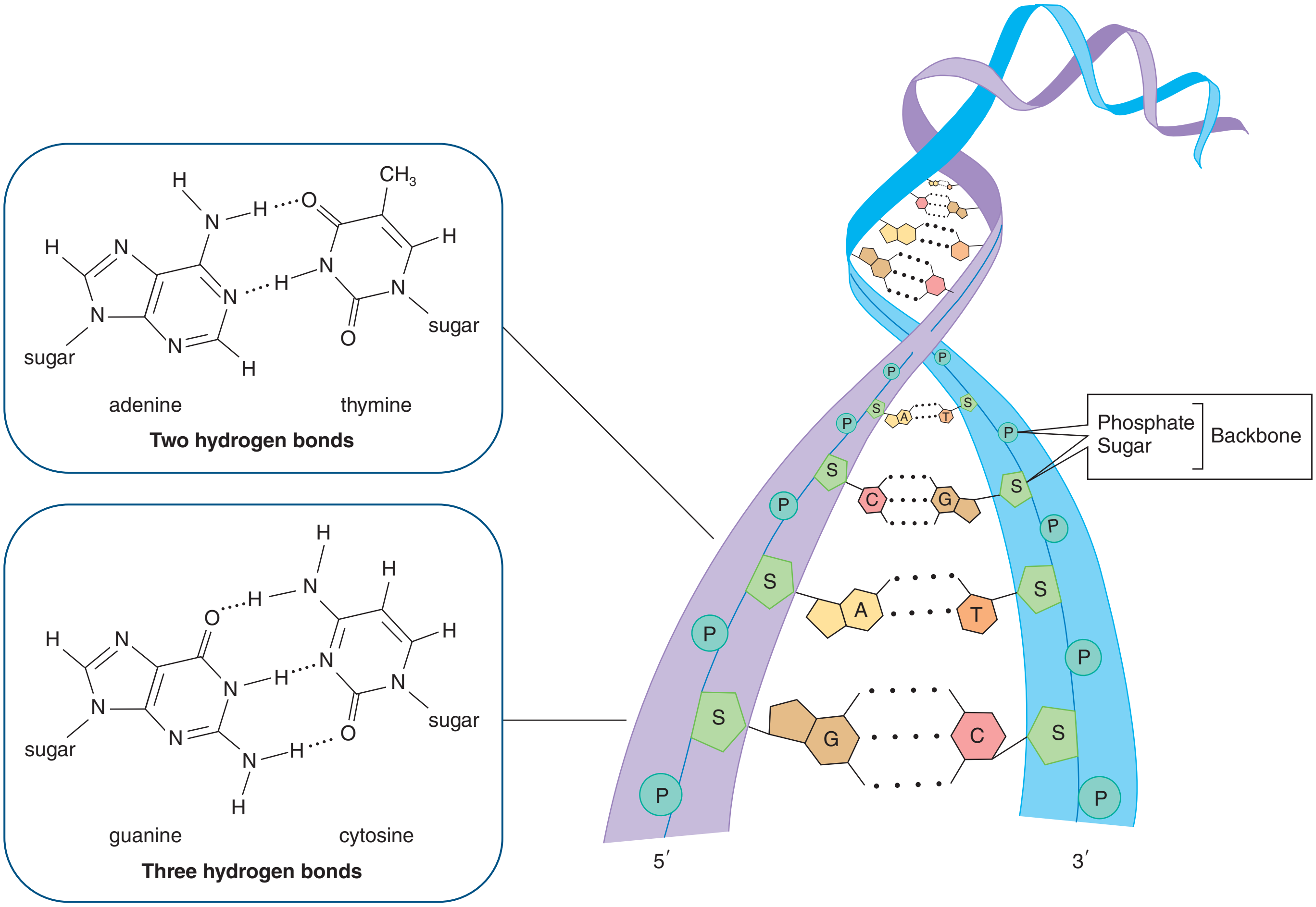


FIGURE 21.8 Base pairing. Hydrogen bonding between complementary base pairs holds the two strands of a DNA molecule together.

Example 21.4 Counting Hydrogen Bonds

How many hydrogen bonds are between ATCCG and its complementary sequence of DNA?

Solution

Every pair of bases AT is held together by two hydrogen bonds, and every pair of bases GC is held together by three hydrogen bonds. The total number is 13 hydrogen bonds.

✔ **LEARNING CHECK 21.4** How many hydrogen bonds are between CACTG and its complementary sequence of DNA?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 21.5 Writing Base Sequences

One strand of a DNA molecule has the base sequence CCATTG. What is the base sequence for the complementary strand?

Solution

Three things must be remembered and used to solve this problem: (1) The base sequence of a DNA strand is always written from the 5′ end to the 3′ end; (2) adenine (A) is always paired with its complementary base thymine (T), and guanine (G) is always paired with its complement cytosine (C); and (3) in double-stranded DNA, the two strands run in opposite directions, so that the 5′ end of one strand is associated with the 3′ end of the other strand. These three ideas lead to the following:

Original strand: 5′ end C–C–A–T–T–G 3′ end

COMPLEMENTARY STRAND: 3′ END G–G–T–A–A–C 5′ END

When we follow convention and write the sequence of the complementary strand in the 5′ to 3′ direction, it becomes

5′ C–A–A–T–G–G 3′

✔ **LEARNING CHECK 21.5** Write the complementary base sequence for the DNA strand TTACG.

21.3 DNA Replication

Learning Objective 3 Outline the process of DNA replication.

DNA is responsible for one of the most essential functions of living organisms, the storage and transmission of hereditary information. A human cell normally contains 46 structural units called **chromosomes** (see **Figure 21.9**). Each chromosome contains one molecule of DNA coiled tightly about a group of small, basic proteins called histones. Individual sections of DNA molecules make up **genes**, the fundamental units of heredity. In **Section 21.5**, you'll learn that each gene directs the synthesis of a specific protein. The number of genes contained in the structural unit of an organism varies with the type of organism. For example, a virus, the smallest structure known to carry genetic information, is thought to contain from a few to several hundred genes. A bacterial cell, such as *Escherichia coli* (*E. coli*), contains about 1000 genes, whereas a human cell contains approximately 25,000. One of the elegant features of the Watson–Crick three-dimensional structure for DNA was that it provided the first satisfactory explanation for the transmission of hereditary information—it explained how DNA is duplicated for the next generation.

chromosome A tightly packed bundle of DNA and protein that is involved in cell division.

gene An individual section of a chromosomal DNA molecule that is the fundamental unit of heredity.

The process by which an exact copy of DNA is produced is called **replication**. It occurs when two strands of DNA separate and each serves as a template (pattern) for the construction of its own complement. The process generates new DNA double-stranded molecules that are exact replicas of the original DNA molecule. A schematic diagram of the replication process is presented in **Figure 21.10**. Notice that the two daughter DNA molecules have exactly the same base sequences as the original parent DNA. Notice, too, that each daughter contains one strand of the parent and one new strand that is complementary to the parent strand. This type of replication is called **semiconservative replication**.

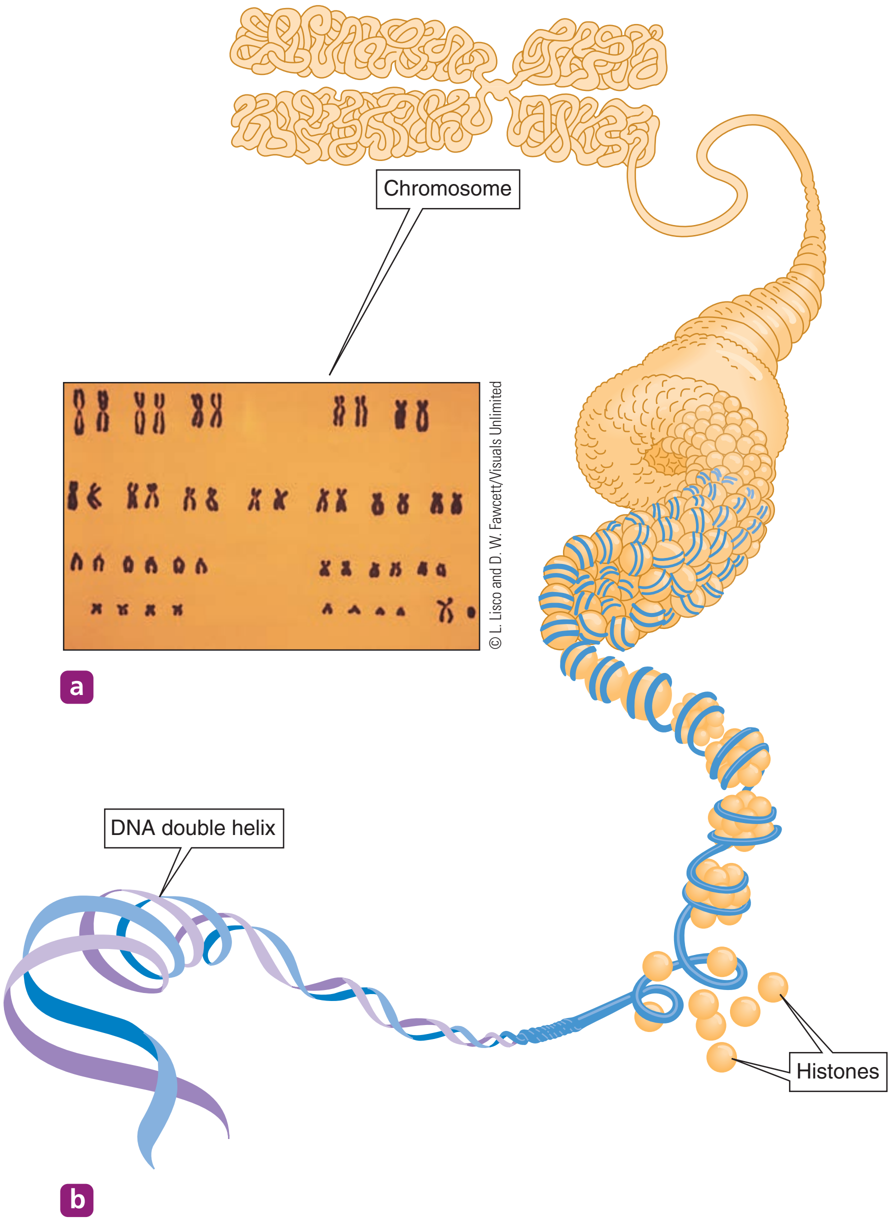
replication The process by which an exact copy of a DNA molecule is produced.

semiconservative replication A replication process that produces DNA molecules containing one strand from the parent and a new strand that is complementary to the strand from the parent.

The process of replication can be viewed as occurring in three steps.

Step 1. Unwinding of the double helix: Replication begins when the enzyme helicase catalyzes the separation and unwinding of the nucleic acid strands at a specific point along the DNA helix. In this process, hydrogen bonds between complementary base pairs are broken, and the bases that were formerly in the center of the helix are exposed. The point where this unwinding takes place is called a **replication fork** (see **Figure 21.11**).

replication fork A point where the double helix of a DNA molecule unwinds during replication.



© L. Lisco and D. W. Fawcett/Visuals Unlimited

FIGURE 21.9 Chromosomes. (**a**) The 46 chromosomes of a human cell. (**b**) Each chromosome is a protein-coated strand of multicoiled DNA.

Step 2. Synthesis of DNA segments: DNA replication takes place along both nucleic acid strands separated in Step 1. The process proceeds from the 3′ end toward the 5′ end of the exposed strand (the template). Because the two strands are antiparallel, the synthesis of new nucleic acid strands proceeds toward the replication fork on one exposed strand and away from the replication fork on the other strand (see **Figure 21.11**). New (daughter) DNA strands form as nucleotides, complementary to those on the exposed strands, and are linked together under the influence of the enzyme DNA polymerase. Notice that the daughter chain grows from the 5′ end toward the 3′ end as the process moves from the 3′ end of the exposed (template) strand toward the 5′ end. As the synthesis proceeds, a second replication fork is created when a new section of DNA unwinds. The daughter strand that was growing toward the first replication fork continues growing smoothly toward the new fork. However, the other daughter strand was growing away from the first fork. A new segment of this strand begins growing from the new fork but is not initially bound to the segment that grew from the first fork. Thus, as the parent DNA progressively unwinds, this daughter strand is synthesized as a series of fragments that are bound together in Step 3. The gaps or breaks between segments in this daughter strand are

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

FIGURE 21.10 A schematic diagram of the replication of DNA.

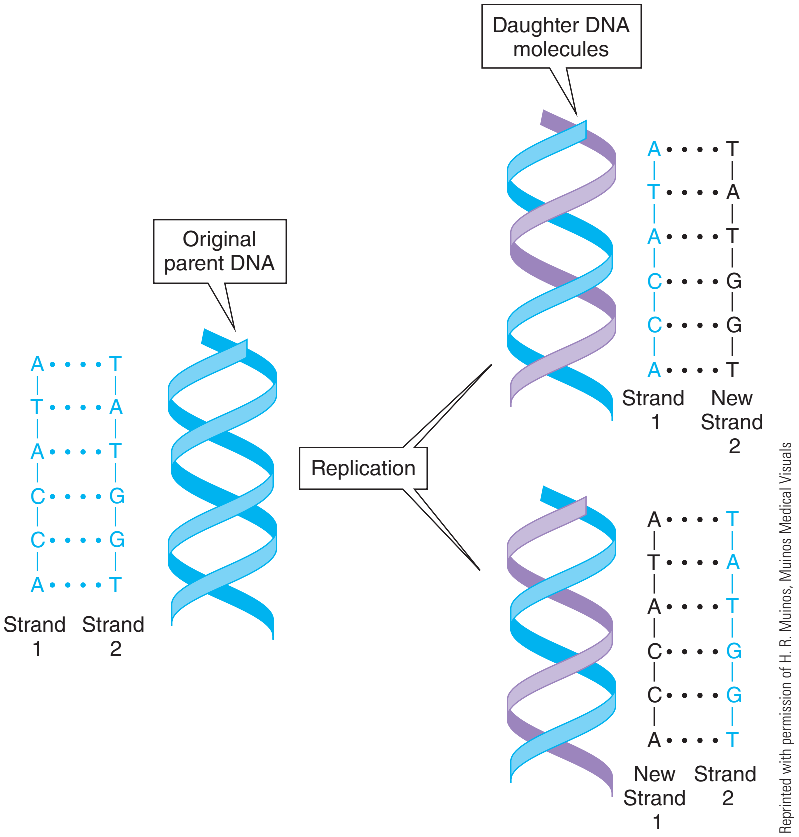
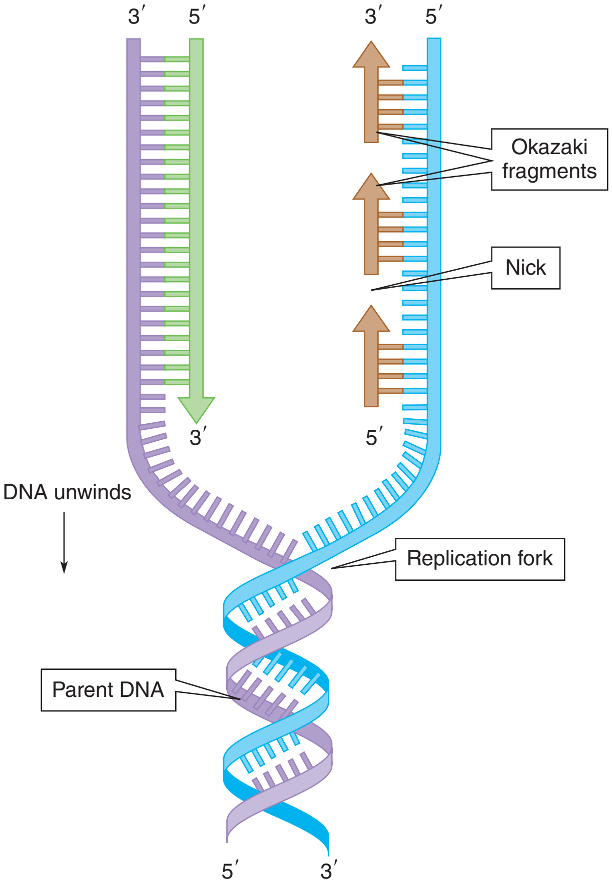

Daughter DNA molecules
Original parent DNA
A T
T A
A T
C G
C G
A T
Strand 1
Strand 2
Replication
Strand 1
New Strand 2
New Strand 1
Strand 2
Reprinted with permission of H. R. Muinos, Muinos Medical Visuals

FIGURE 21.11 The replication of DNA. Both new strands are growing in the 5′ to 3′ direction.


3′
5′
3′
5′
Okazaki fragments
Nick
3′
5′
DNA unwinds
Replication fork
Parent DNA
5′
3′

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

called nicks, and the DNA fragments separated by the nicks are called **Okazaki fragments** after their discoverer, Reiji Okazaki (**Figure 21.11**).

Step 3. Closing the nicks: One daughter DNA strand is synthesized without any nicks, but the Okazaki fragments of the other strand must be joined together. An enzyme called DNA ligase catalyzes this final step of DNA replication. The result is two DNA double-helical molecules that are identical.

Okazaki fragment A DNA fragment produced during replication as a result of strand growth in a direction away from the replication fork.

Observations with an electron microscope show that the replication of DNA molecules in eukaryotic cells occurs simultaneously at many points along the original DNA molecule. These replication zones blend together as the process of replication continues. This is necessary if long molecules are to be replicated rapidly. For example, it is estimated that the replication of the largest chromosome in *Drosophila* (the fruit fly) would take more than 16 days if there were only one origin for replication. Research results indicate that the actual replication is accomplished in less than 3 minutes because it takes place simultaneously at more than 6000 replication forks per DNA molecule. **Figure 21.12** shows a schematic diagram in which replication is proceeding at several points in the DNA chain.

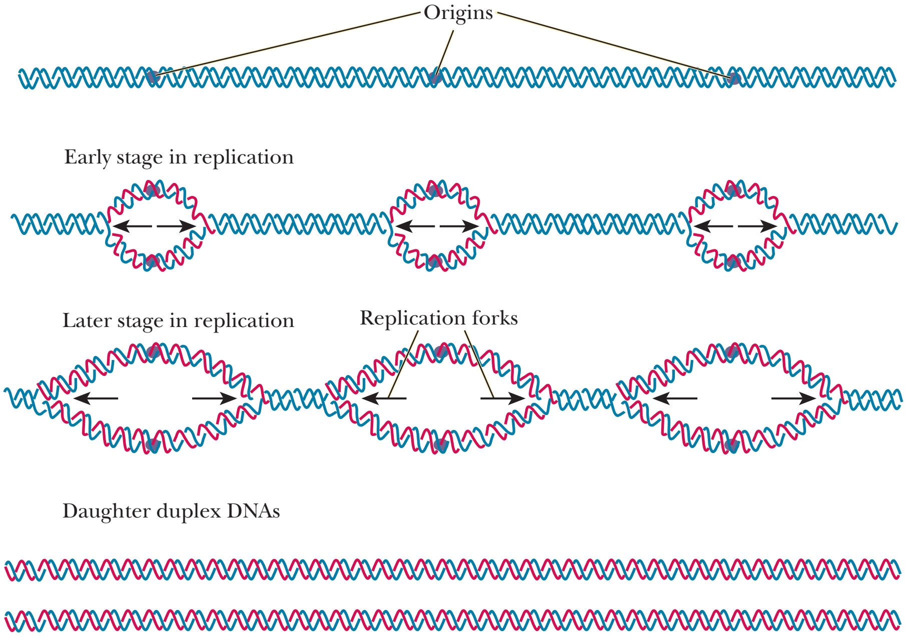


FIGURE 21.12 A schematic representation of eukaryotic chromosome replication, showing several replication forks. From Campbell, *Biochemistry*, 8E. © 2018 Cengage Learning.

A knowledge of the DNA replication process led scientist Kary Mullis in 1983 to a revolutionary laboratory technique called the *polymerase chain reaction (PCR)*. The PCR technique mimics the natural process of replication, in which the DNA double helix unwinds. As the two strands separate, DNA polymerase makes a copy using each strand as a template. To perform PCR, a small quantity of the target DNA is added to a test tube along with a buffered solution containing DNA polymerase; the cofactor $MgCl_2$, which is needed by the polymerase to function; the four nucleotides; the four building blocks; and primers. The primers are short polynucleotide segments that will bind to the separated DNA strands and serve as starting points for new chain growth. The PCR mixture is taken through three-step replication cycles:

1. Heat (94°C–96°C) is used for one to several minutes to unravel (denature) the DNA into single strands.
2. The tube is cooled to 50°C–65°C for one to several minutes, during which the primers hydrogen-bond to the separated strands of target DNA.

3. The tube is heated to 72°C for one to several minutes, during which time the DNA polymerase synthesizes new strands.

Each cycle doubles the amount of DNA. Following 30 such cycles, a theoretical amplification factor of 1 billion is attained.

Almost overnight, PCR became a standard research technique for detecting all manner of mutations associated with genetic disease (see **Section 21.9**). PCR can also be used to detect the presence of unwanted DNA, as in the case of a bacterial or viral infection. Conventional tests that involve the culture of microorganisms or the use of antibodies can take weeks to perform. PCR offers a fast and simple alternative. The ability of PCR to utilize degraded DNA samples and sometimes the DNA from single cells is of great interest to forensic scientists. PCR has also permitted DNA to be amplified from some unusual sources, such as extinct mammals, Egyptian mummies, and ancient insects trapped in amber.

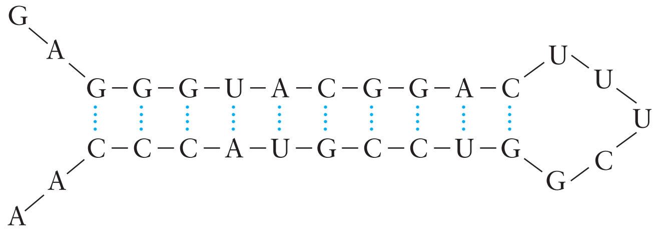
21.4 Ribonucleic Acid (RNA)

Learning Objective 4 Contrast the structures of DNA and RNA and list the function of the three main types of cellular RNA.

RNA, like DNA, is a long, unbranched polymer consisting of nucleotides joined by $3' \rightarrow 5'$ phosphodiester bonds. The number of nucleotides in an RNA molecule ranges from as few as 73 to many thousands. The primary structure of RNA differs from that of DNA in two ways. As we learned in **Section 21.1**, the sugar unit in RNA is ribose rather than deoxyribose. The other difference is that RNA contains the base uracil (U) instead of thymine (T).

The secondary structure of RNA is also different from that of DNA. RNA molecules are single-stranded, except in some viruses. Consequently, an RNA molecule need not contain complementary base ratios of 1:1. However, RNA molecules do contain regions of double-helical structure where they form loops (see **Figure 21.13**). In these regions, adenine (A) pairs with uracil (U), and guanine (G) pairs with cytosine (C). The proportion of helical regions varies over a wide range depending on the kind of RNA studied, but a value of 50% is typical.

FIGURE 21.13 A portion of RNA that has folded back on itself and formed a double-helical region.



RNA is distributed throughout cells; it is present in the nucleus, the cytoplasm, and in mitochondria (see **Table 18.3** and **Section 22.7**). Cells contain three main kinds of RNA: messenger RNA (mRNA), ribosomal RNA (rRNA), and transfer RNA (tRNA). Each of these kinds of RNA performs an important function in protein synthesis.

21.4A Messenger RNA

messenger RNA (mRNA) RNA that carries genetic information from the DNA in the cell nucleus to the site of protein synthesis in the cytoplasm.

Messenger RNA (mRNA) functions as a carrier of genetic information from the DNA of the cell nucleus directly to the cytoplasm, where protein synthesis takes place. The bases of mRNA are in a sequence that is complementary to the base sequence of one of the strands of the nuclear DNA. In contrast to DNA, which remains intact and unchanged throughout the life of the cell, mRNA has a short lifetime—usually less than an hour. It is synthesized as needed and then rapidly degraded to the constituent nucleotides.

21.4B Ribosomal RNA

Ribosomal RNA (rRNA) constitutes 80–85% of the total RNA of the cell. It is located in the cytoplasm in organelles called **ribosomes**, which are about 65% rRNA and 35% protein (see **Figure 21.14**). The function of ribosomes as the sites of protein synthesis is discussed in **Section 21.8**.

ribosomal RNA (rRNA) RNA that constitutes about 65% of the material in ribosomes, the sites of protein synthesis.

ribosome A subcellular particle that serves as the site of protein synthesis in all organisms.

dpa picture alliance/Alamy Stock Photo

FIGURE 21.14 Ada Yonath, an Israeli crystallographer, received the 2009 Nobel Prize in Chemistry for her pioneering work on the structure of ribosomes.

21.4C Transfer RNA

Transfer RNA (tRNA) molecules deliver amino acids, the building blocks of proteins, to the site of protein synthesis. Cells contain at least one specific type of tRNA for each of the 20 common amino acids found in proteins. These tRNA molecules are the smallest of all the nucleic acids, containing 73–93 nucleotides per chain.

A comparison of RNA characteristics for the three different forms is summarized in **Table 21.1**.

TABLE 21.1 Different Forms of RNA Molecules in *E. coli*

Class of RNA	% in Cells	Number of RNA Subtypes	Number of Nucleotides
Ribosomal RNA (rRNA)	80	3	120
			1700
			3700
Transfer RNA (tRNA)	15	46	73–93
Messenger RNA (mRNA)	5	Many	75–3000

transfer RNA (tRNA) RNA that delivers individual amino acid molecules to the site of protein synthesis.

Because of their small size, a number of tRNAs have been studied extensively. **Figure 21.15** shows a representation of the secondary structure of a typical tRNA: This tRNA molecule, like all others, has regions where there is hydrogen bonding between complementary bases, and regions (loops) where there is no hydrogen bonding.

Two regions of tRNA molecules have important functions during protein synthesis. One of these regions, designated the **anticodon**, enables the tRNA to bind to mRNA during protein synthesis. The second important site is the 3′ end of the molecule, which binds to an amino acid and transports it to the site of protein synthesis. Each amino acid is joined to the 3′ end of its specific tRNA by an ester bond that forms between the carboxyl group of the amino acid and the 3′ hydroxy group of ribose. The reaction is catalyzed by an enzyme that matches tRNA molecules to their proper amino acids. These enzymes, which are very specific for both the structure of the amino acid and the tRNA, rarely cause a bond to form between an amino acid and the wrong tRNA. When a tRNA molecule is attached to its specific amino acid, it is said to be "activated" because it is ready to participate in protein synthesis. **Figure 21.16** shows the general structure of an activated tRNA and a schematic representation that will be used in **Section 21.8** to describe protein synthesis.

anticodon A three-base sequence in tRNA that is complementary to one of the codons in mRNA.

FIGURE 21.15 The typical tRNA cloverleaf structure.

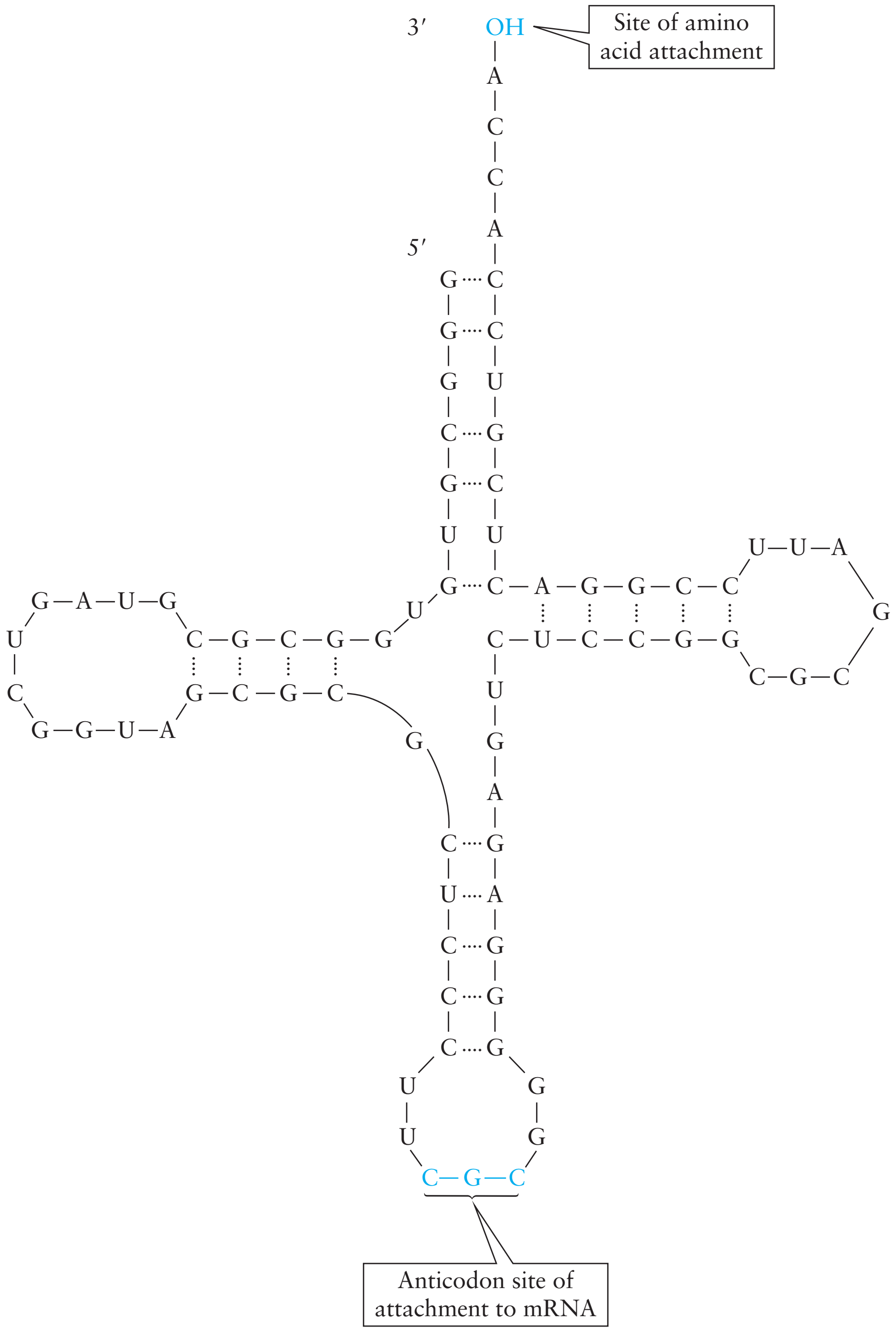
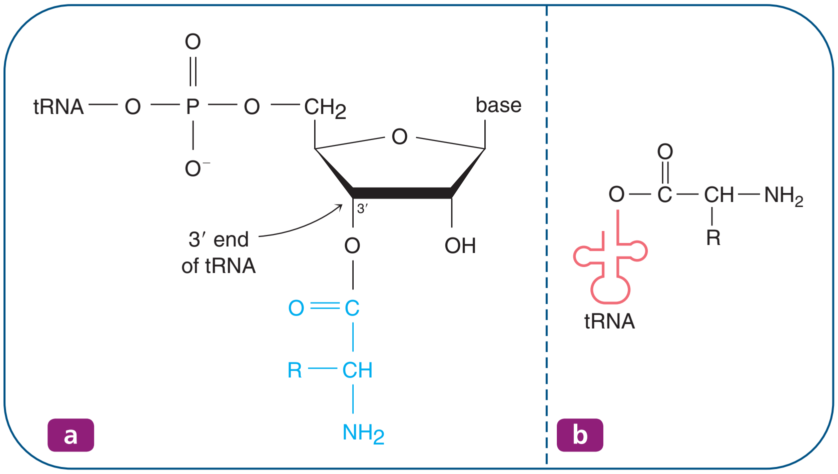

3′
OH
Site of amino acid attachment
A
C
C
A
5′
G–G–G–C–G–U–G
C–C–U–G–C–U–C
U
G–A–U–G
U
C
G–G–U–A
C–G–C–G–G
G–C–G–C
G
A–G–G–C–C
U–U–A
G
C–G–C
C–U–C–C–G–G
U
G
A
C–U–C–C–C
G–A–G–G–G
U
U
G
G
C–G–C
Anticodon site of attachment to mRNA

FIGURE 21.16 An activated tRNA: (**a**) general structure and (**b**) a schematic representation.


tRNA
O
P
O⁻
CH2
base
O
3′
3′ end of tRNA
OH
O=C
R–CH
NH2
a
O–C–CH–NH2
R
tRNA
b

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

21.4D Other Types of RNA

In addition to the three main types of cellular RNA, scientists have discovered there are small, non-coding RNAs (ncRNA). These ncRNA are typically less than 200 nucleotides long and are not translated into protein. They were once considered to be "junk" RNA with no function. We now know there are many types of small ncRNA with important functions. The most common function for these small RNA strands involves RNA interference, where these ncRNA molecules inhibit gene expression by interfering with translation of a messenger RNA strand. RNA interference is often used by scientists to better understand what genes are involved in certain pathways and what genes are important in disease. Studies suggest there are thousands of different ncRNAs.

21.5 The Flow of Genetic Information

Learning Objective 5 Describe what is meant by the terms *transcription* and *translation*.

You learned in **Section 21.3** that DNA is the storehouse of genetic information in the cell and that the stored information can be passed on to new cells as DNA undergoes replication. In this section, you will discover how the information stored in DNA is expressed within the cell.

This process of expression is so well established that it is called the **central dogma of molecular biology**. The accepted dogma, or principle, says that genetic information contained in DNA molecules is transferred to RNA molecules. The transferred information of RNA molecules is then expressed in the structure of synthesized proteins. In other words, the genetic information in DNA (genes) directs the synthesis of certain proteins. In fact, there is a specific DNA gene for every protein in the body. DNA does not direct the synthesis of carbohydrates, lipids, or the other nonprotein substances essential for life. However, these other materials are manufactured by the cell through reactions made possible by enzymes (proteins) produced under the direction of DNA. Thus, in this respect, the information stored in DNA really does determine every characteristic of the living organism.

central dogma of molecular biology The well-established process by which genetic information stored in DNA molecules is expressed in the structure of synthesized proteins.

Two steps are involved in the flow of genetic information: transcription and translation. In higher organisms (eukaryotes), the DNA containing the stored information is located in the nucleus of the cell, and protein synthesis occurs in the cytoplasm. Thus, the stored information must first be carried out of the nucleus. This is accomplished by **transcription**, or transferring the necessary information from a DNA molecule onto a molecule of messenger RNA. The appropriately named messenger RNA carries the information (the message) from the nucleus to the site of protein synthesis in the cellular cytoplasm.

transcription The transfer of genetic information from a DNA molecule to a molecule of messenger RNA.

In the second step, the mRNA serves as a template on which amino acids are assembled in the proper sequence necessary to produce the specified protein. This takes place when the code or message carried by mRNA is translated into an amino acid sequence by tRNA. There is an exact word-to-word **translation** from mRNA to tRNA. Thus, each word in the mRNA language has a corresponding word in the amino acid language of tRNA. This communicative relationship between mRNA nucleotides and amino acids is called the *genetic code* (see **Section 21.7**). **Figure 21.17** summarizes the mechanisms for the flow of genetic information in the cell.

translation The conversion of the code carried by messenger RNA into an amino acid sequence of a protein.

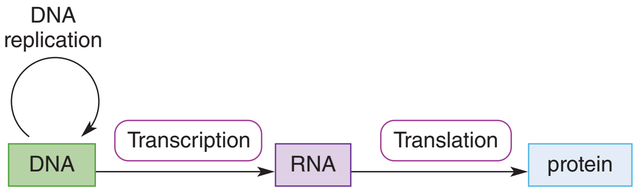


FIGURE 21.17 The flow of genetic information in the cell.

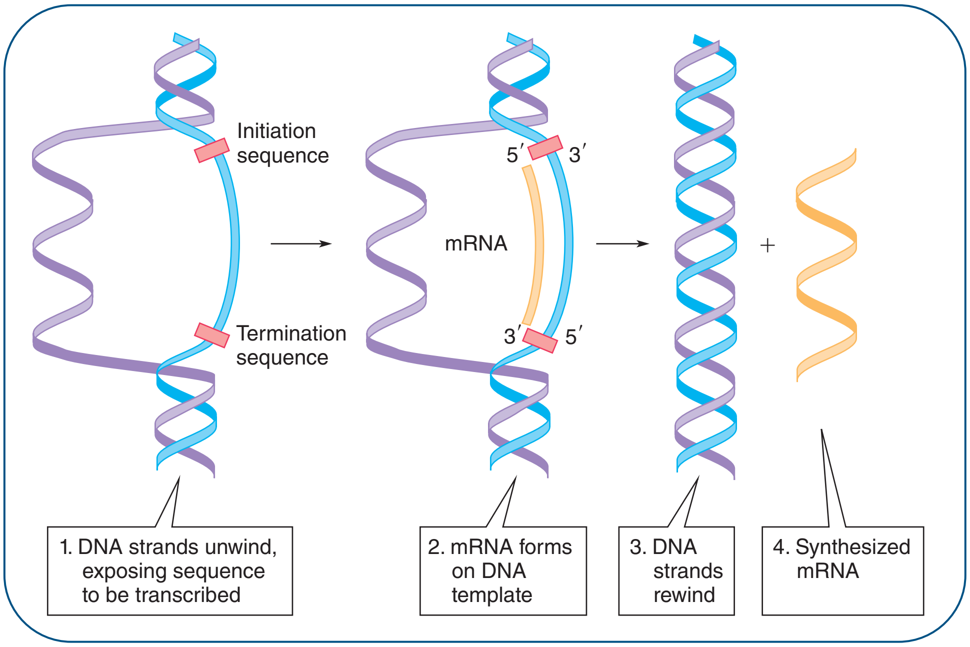
21.6 Transcription: RNA Synthesis

Learning Objective 6 Describe the process by which RNA is synthesized in cells.

An enzyme called RNA polymerase catalyzes the synthesis of RNA. During the first step of the process, the DNA double helix begins to unwind at a point near the gene that is to be transcribed. Since the end product will be single-stranded, only one strand of the DNA molecule is transcribed. Ribonucleotides are linked together along the unwound DNA strand in a sequence determined by complementary base pairing of the DNA strand bases and ribonucleotide bases.

The DNA strand always has one sequence of bases recognized by RNA polymerase as the initiation or starting point. Starting at this point, the enzyme catalyzes the synthesis of mRNA in the 5′ to 3′ direction until it reaches another sequence of bases that designates the termination point. Because the complementary chains of RNA and DNA run in opposite directions, the enzyme must move along the DNA template in the 3′ to 5′ direction (see **Figure 21.18**). Once the mRNA molecule has been synthesized, it moves away from the DNA template, which then rewinds to form the original double-helical structure. Transfer RNA and ribosomal RNA are synthesized in the same way, with DNA serving as a template.

FIGURE 21.18 The synthesis of mRNA.



Example 21.6 Writing RNA Sequences

Write the sequence for the mRNA that could be synthesized using the following DNA base sequence as a template:

5′ G–C–A–A–C–T–T–G 3′

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Solution

RNA synthesis begins at the 3′ end of the DNA template and proceeds toward the 5′ end. The complementary RNA strand is formed from the bases C, G, A, and U. Uracil (U) is the complement of adenine (A) on the DNA template.

direction of strand →
DNA template: 5′ G–C–A–A–C–T–T–G 3′
New mRNA: 3′ C–G–U–U–G–A–A–C 5′
← direction of strand

Writing the sequence of the new mRNA in the 5′ to 3′ direction, it becomes:

5′ C–A–A–G–U–U–G–C 3′

✔ LEARNING CHECK 21.6 Write the sequence for the mRNA that could be synthesized on the following DNA template:

5′ A–T–T–A–G–C–C–G 3′

Although the general process of transcription operates universally, there are differences in detail between the processes in prokaryotes and eukaryotes. The genes found in prokaryotic cells exist as a continuous segment of a DNA molecule. Transcription of this gene segment produces mRNA that undergoes translation into a protein almost immediately because there is no nuclear membrane in a prokaryotic cell separating DNA from the cytoplasm. In 1977, however, it was discovered that the genes of eukaryotic cells are segments of DNA that are "interrupted" by segments that do not code for amino acids. These DNA segments that carry no amino acid code are called **introns**, and the coded DNA segments are called **exons**.

When transcription occurs in the nuclei of eukaryotic cells, both introns and exons are transcribed. This produces what is called **heterogeneous nuclear RNA (hnRNA)**. This long molecule of hnRNA then undergoes a series of enzyme-catalyzed reactions that cut and splice the hnRNA to produce mRNA (see **Figure 21.19**). The mRNA resulting from this process contains only the sequence of bases that actually codes for protein synthesis. Although the function of introns in eukaryotic DNA is not yet understood, it is an area of active research.

intron A segment of a eukaryotic DNA molecule that carries no codes for amino acids.

exon A segment of a eukaryotic DNA molecule that is coded for amino acids.

heterogeneous nuclear RNA (hnRNA) RNA produced when both introns and exons of eukaryotic cellular DNA are transcribed.

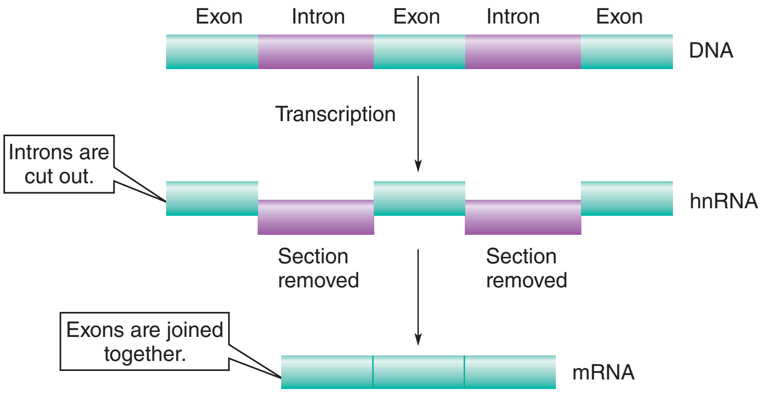


FIGURE 21.19 Segments of hnRNA formed from introns of eukaryotic cells are removed by special enzymes to produce mRNA.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS **21.1**

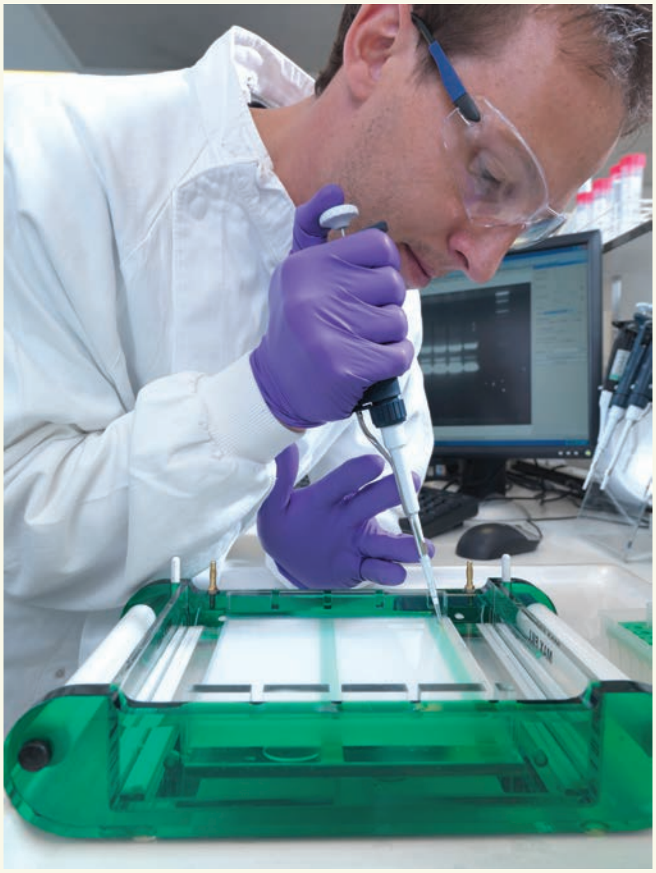
Is There a DNA Checkup in Your Future?

Today, the work of reading a human genome—which initially required thousands of scientists much more than 10 years to accomplish at a cost of $2.7 billion—can be done in one lab in a matter of hours at a cost of $100.

What is the benefit of knowing the genome of a human? In 2000, only a handful of genes had been identified that were known to influence the development of common diseases such as heart disease, diabetes, and some cancers. Today, as a result of research in the Human Genome Project, the number of such predictive genes has increased to 600–700 and involves more than 100 diseases.

While it is probably a number of years in the future, one clinical expectation from the Human Genome Project is that physicians will one day be able to prescribe personal genome readings for patients. The results of such DNA checkups might allow physicians to precisely estimate individual risks for a significant number of common diseases and then provide advice on lifestyle changes, or even prescribe preventive medications.

Continuing efforts are underway to reduce the costs associated with DNA-sequencing equipment and procedures to bring them in line with the costs of relatively routine diagnostic procedures. So, it appears probable that DNA checkups are likely to be in your future, especially if you are relatively young.


Cultura Limited/Superstock

A researcher prepares a sample for DNA sequencing.

21.7 The Genetic Code

Learning Objective 7 Explain how the genetic code functions in the flow of genetic information.

21.7A Discovery of the Genetic Code

By 1961, it was clear that the sequence of bases in DNA serves to direct the synthesis of mRNA, and that the sequence of bases in mRNA corresponds to the order of amino acids in a particular protein. However, the genetic code, the exact relationship between mRNA sequences and amino acids, was unknown. At least 20 mRNA "words" are needed to represent uniquely each of the 20 amino acids found in proteins. If the mRNA words consisted of a single letter represented by a base (A, C, G, or U), only four amino acids could be uniquely represented. Thus, it was proposed that it is not one mRNA base but a combination of bases that codes for each amino acid. For example, if a code word consists of a sequence of two mRNA bases, there are $4^2 = 16$ possible combinations, so 16 amino

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

acids could be represented uniquely. This is a more extensive code, but it still contains too few words to do the job for 20 amino acids. If the code consists of a sequence of three bases, there are $4^3 = 64$ possible combinations, more than enough to specify uniquely each amino acid in the primary sequence of a protein. Research has confirmed that nature does indeed use three-letter code words (a triplet code) to store and express genetic information. Each sequence of three nucleotide bases that represents code words on mRNA molecules is called a **codon**.

codon A sequence of three nucleotide bases that represents a code word on mRNA molecules.

After the discovery of three-letter codons, researchers were anxious to answer the next question: Which triplets of bases (codons) code for which amino acids? In 1961, Marshall Nirenberg and his co-workers at the National Institutes of Health (NIH) in Bethesda, Maryland, attempted to break the code in a very ingenious way. They made a synthetic molecule of mRNA consisting of uracil bases only. Thus, this mRNA contained only one codon, the triplet UUU. They incubated this synthetic mRNA with ribosomes, amino acids, tRNAs, and the appropriate enzymes for protein synthesis. The exciting result of this experiment was that a polypeptide that consisted only of phenylalanine was synthesized. Thus, the first word of the genetic code had been deciphered; UUU phenylalanine.

A series of similar experiments by Nirenberg and other researchers followed, and by 1967 the entire genetic code had been broken. The complete code is shown in **Table 21.2**.

TABLE 21.2 The Genetic Code: mRNA Codons for Each of the 20 Amino Acids

Amino Acid	Codons	Number of Codons
Alanine	GCA, GCC, GCG, GCU	4
Arginine	AGA, AGG, CGA, CGC, CGG, CGU	6
Asparagine	AAC, AAU	2
Aspartic acid	GAC, GAU	2
Cysteine	UGC, UGU	2
Glutamic acid	GAA, GAG	2
Glutamine	CAA, CAG	2
Glycine	GGA, GGC, GGG, GGU	4
Histidine	CAC, CAU	2
Isoleucine	AUA, AUC, AUU	3
Leucine	CUA, CUC, CUG, CUU, UUA, UUG	6
Lysine	AAA, AAG	2
Methionine, initiation	AUG	1
Phenylalanine	UUC, UUU	2
Proline	CCA, CCC, CCG, CCU	4
Serine	UCA, UCC, UCG, UCU, AGC, AGU	6
Threonine	ACA, ACC, ACG, ACU	4
Tryptophan	UGG	1
Tyrosine	UAC, UAU	2
Valine	GUA, GUC, GUG, GUU	4
Stop signals	UAG, UAA, UGA	3
Total number of codons		64

STUDY TOOLS 21.1

Remembering Key Words

Three very important processes discussed in this chapter are replication, transcription, and translation. New terminology is always easier to learn if we can make associations with something we already know. See if these ideas help. To replicate means to copy or to repeat. Associate the word *replicate* with *repeat*.

For the processes of transcription and translation, think of an analogy with the English language. If you were to transcribe your lecture notes from a recording, you would rewrite them in the same language. In the same way, transcription of DNA to mRNA is a rewriting of the information using the same nucleic acid language. If you translated your lecture notes, you would convert them to another language, such as German. Translation of mRNA to an amino acid sequence is converting information from a nucleic acid language to a language of proteins.

21.7B Characteristics of the Genetic Code

The first important characteristic of the genetic code is that it applies almost universally. With very minor exceptions, the same amino acid is represented by the same three-base codon (or codons) in every organism.

Another interesting feature of the genetic code is apparent from **Table 21.2**. Most of the amino acids are represented by more than one codon, a condition known as *degeneracy*. Only methionine and tryptophan are represented by single codons. Leucine, serine, and arginine are the most degenerate, with each one represented by six codons. The remaining 15 amino acids are each coded for by at least two codons. Even though most amino acids are represented by more than one codon, it is significant that the reverse is not true—no single codon represents more than one amino acid. Each three-base codon represents one and only one amino acid.

Only 61 of the possible 64 base triplets represent amino acids. The remaining three (UAA, UAG, and UGA) are signals for chain terminations. They tell the protein-synthesizing process when the primary structure of the synthesized protein is complete and it is time to stop adding amino acids to the chain. These three codons are indicated in **Table 21.2** as stop signals.

The presence of stop signals in the code implies that start signals must also exist. There is only one initiation (start) codon, AUG, which also is the codon for the amino acid methionine. AUG functions as an initiation codon only when it occurs as the first codon of a sequence. When this happens, protein synthesis begins at that point (see **Section 21.8**).

These general features of the genetic code are summarized in **Table 21.3**.

TABLE 21.3 General Characteristics of the Genetic Code

Characteristic	Example
Codons are three-letter words.	GCA = alanine
The code is degenerate.	GCA, GCC, GCG, GCU all represent alanine
The code is precise.	GCC represents only alanine
Chain initiation is coded.	AUG = methionine
Chain termination is coded.	UAA, UAG, and UGA
The code is almost universal.	GCA = alanine, perhaps, in all organisms

21.8 Translation and Protein Synthesis

Learning Objective 8 Outline the process by which proteins are synthesized in cells.

To this point, you have become familiar with the molecules that participate in protein synthesis and the genetic code, the language that directs the synthesis. We now investigate the actual process by which polypeptide chains are assembled. There are three major stages in protein synthesis (see **Figure 21.20**): initiation of the polypeptide chain, elongation of the chain, and termination of the completed polypeptide chain.

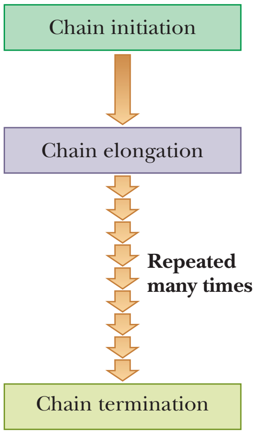
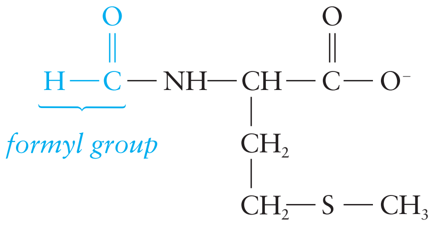


FIGURE 21.20 The stages of protein synthesis. From Campbell, *Biochemistry*, 8E. © 2018 Cengage Learning.

21.8A Initiation of the Polypeptide Chain

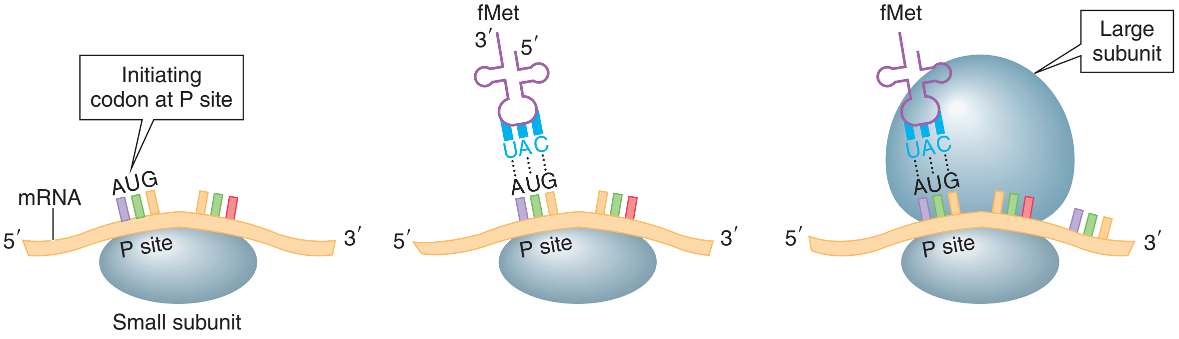
The first amino acid that starts the process of protein synthesis in prokaryotic (bacterial) cells is a derivative of methionine. This compound, *N*-formylmethionine, initiates the growing polypeptide chain as the N-terminal amino acid. The fact that most proteins do not have *N*-formylmethionine as the N-terminal amino acid indicates that when protein synthesis is completed, the *N*-formylmethionine is cleaved from the finished protein.



$$\underbrace{H-\overset{\overset{O}{\|}}{C}}_{\text{formyl group}}-NH-\underset{\substack{|\\CH_2\\|\\CH_2-S-CH_3}}{CH}-\overset{\overset{O}{\|}}{C}-O^-$$

N-formylmethionine
(fMet)

A ribosome comprises two subunits, a large subunit and a small subunit. The initiation process begins when mRNA is aligned on the surface of a small ribosomal subunit in such a way that the initiating codon, AUG, occupies a specific site on the ribosome called the P site (peptidyl site). When the AUG codon is used this way to initiate synthesis of a polypeptide chain in prokaryotic cells, it represents *N*-formylmethionine (fMet) instead of methionine. When AUG is located anywhere else on the mRNA, it simply represents methionine. For the eukaryotic cells of humans, AUG always specifies methionine even when it is the initiating codon. Next, a tRNA molecule with its attached fMet binds to the codon through hydrogen bonds. The resulting complex binds to the large ribosomal subunit to form a unit called an *initiation complex* (see **Figure 21.21**).



1 mRNA aligns on a small ribosomal subunit so that AUG, the initiating codon, is at the ribosomal P site.

2 A tRNA with an attached *N*-formylmethionine forms hydrogen bonds with the codon.

3 A large ribosomal subunit binds to the small subunit and completes the initiation complex.

FIGURE 21.21 Initiation complex formation.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

21.8B Elongation of the Chain

A second site, called the A site (aminoacyl site), is located on the mRNA–ribosome complex next to the P site. The A site is where an incoming tRNA carrying the next amino acid will bond. Each of the tRNA molecules representing the 20 amino acids can try to fit the A site, but only the one with the correct anticodon that is complementary to the next codon on the mRNA will fit properly.

Once at the A site, the second amino acid (in this case, phenylalanine) is linked to *N*-formylmethionine by a peptide bond whose formation is catalyzed by the enzyme peptidyl transferase (see **Figure 21.22**). After the peptide bond forms, the tRNA bound to the P site is "empty," and the growing polypeptide chain is now attached to the tRNA bound to the A site.

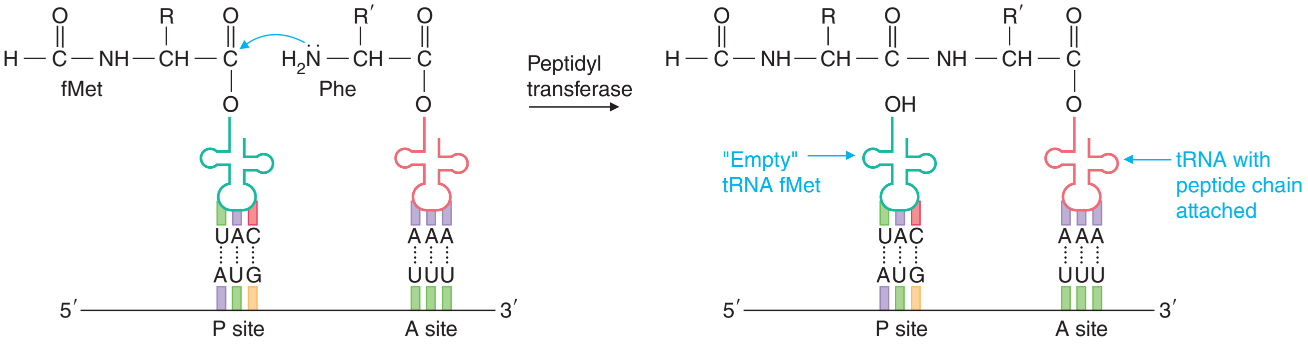
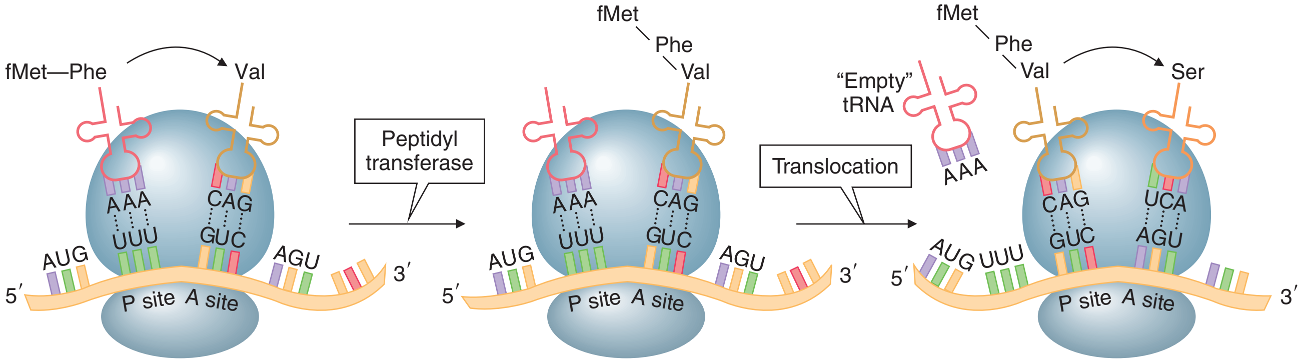


FIGURE 21.22 The amino acid at the P site bonds through a peptide bond to the amino acid at the A site.

In the next phase of elongation, the whole ribosome moves one codon along the mRNA toward the 3′ end. As the ribosome moves, the empty tRNA is released from the P site, and tRNA attached to the peptide chain moves from the A site and takes its place on the P site. This movement of the ribosome along the mRNA is called *translocation* and makes the A site available to receive the next tRNA with the proper anticodon. The amino acid carried by this tRNA bonds to the peptide chain, and the elongation process is repeated. This occurs over and over until the entire polypeptide chain is synthesized. The elongation process is represented in **Figure 21.23** for the synthesis of the tripeptide fMet—Phe—Val.



1 The P site is occupied by the tRNA with the growing peptide chain, and Val—tRNA is located at the A site.

2 The formation of a peptide bond between Val and the dipeptide fMet—Phe takes place under the influence of peptidyl transferase.

3 During translocation when the ribosome shifts to the right, the empty tRNA leaves, the polypeptide—tRNA moves to the P site, and the next tRNA carrying Ser arrives at the A site.

FIGURE 21.23 Polypeptide chain elongation.

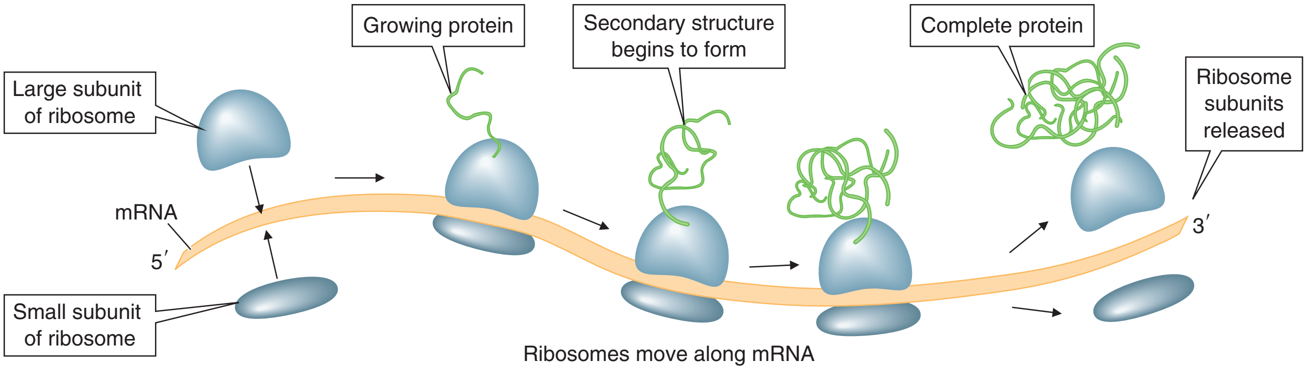
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

21.8C The Termination of Polypeptide Synthesis

The chain elongation process continues and polypeptide synthesis continues until the ribosome complex reaches a stop codon (UAA, UAG, or UGA) on the mRNA. At that point, a specific protein known as a termination factor binds to the stop codon and catalyzes the hydrolysis of the completed polypeptide chain from the final tRNA. The "empty" ribosome dissociates and can then bind to another strand of mRNA to once again begin the process of protein synthesis.

Several ribosomes can move along a single strand of mRNA one after another (see **Figure 21.24**). Thus, several identical polypeptide chains can be synthesized almost simultaneously from a single mRNA molecule. This markedly increases the efficiency of utilization of the mRNA. Such complexes of several ribosomes and mRNA are called **polyribosomes** or **polysomes**. Growing polypeptide chains extend from the ribosomes into the cellular cytoplasm and spontaneously fold to assume characteristic three-dimensional secondary and tertiary configurations.

polyribosome or polysome A complex of mRNA and several ribosomes.



Growing protein
Secondary structure begins to form
Complete protein
Large subunit of ribosome
Ribosome subunits released
mRNA
5′
3′
Small subunit of ribosome
Ribosomes move along mRNA

FIGURE 21.24 A polyribosome, several ribosomes proceeding simultaneously along mRNA.

Example 21.7 Translating Polypeptide Structures

Write the primary structure of the polypeptide produced during translation of the following mRNA sequence:

5′ AUG-UUG-GAG-AAA-GUA-GGA 3′

Solution

met-leu-glu-lys-val-gly

✔ **LEARNING CHECK 21.7** Write the primary structure of the polypeptide produced during translation of the following mRNA sequence:

5′ AUG–CAC–CAU–GUA–UUG–UGU–UAG 3

21.9 Mutations

Learning Objective 9 Describe how genetic mutations occur and how they influence organisms.

In **Section 21.3**, we pointed out that the base-pairing mechanism provides a nearly perfect way to copy a DNA molecule during replication. However, not even the copying mechanism involved in DNA replication is totally error free. It is estimated that, on average, one in every 10^{10} bases of DNA (i.e., 1 in 10 billion) is incorrect. Any change resulting in an incorrect sequence of bases on DNA is called a **mutation**. The faithful transcription of mutated DNA leads to an incorrect base sequence in mRNA. This can lead to an incorrect amino acid sequence for a protein, or possibly the failure of a protein to be synthesized at all.

mutation Any change resulting in an incorrect base sequence on DNA.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

There are three main types of mutations that result in translatable damage to DNA. The first is called a base substitution, where a single base is substituted for another base. For example, if a *GAA* is mutated to *GGA* in the coding region of DNA, this causes a change in a protein from a glutamic acid to a glycine. The second type of mutation is called a deletion, where one or more nucleotides are deleted from DNA. This can cause a change in the reading frame such that the protein product made is truncated or non functional. The third type of mutation is called an insertion-where extra nucleotides are added to a DNA region, which also often leads to a non functional protein product.

Some mutations occur naturally during DNA replication; others can be induced by environmental factors such as ionizing radiation (X-rays, ultraviolet light, gamma rays, etc.). Repeated exposure to X-rays greatly increases the rate of mutation. Thus, patients are given X-rays only when necessary, and technicians who administer X-rays remain behind protective barriers. A large number of chemicals (e.g., nitrous acid and dimethyl sulfate) can also induce mutations by reacting with DNA. Such chemicals are called **mutagens**.

mutagen A chemical that induces mutations by reacting with DNA.

Some mutations might be beneficial to an organism by making it more capable of surviving in its environment. Mutations may also occur without affecting an organism. Conversely, mutations may be lethal or produce genetic diseases whenever an important protein (or enzyme) is not correctly synthesized. Sickle-cell disease, phenylketonuria (PKU), hemophilia, muscular dystrophy, and many other disorders are results of such mutations that have become permanently incorporated into the genetic makeup of certain individuals.

21.10 Recombinant DNA

Learning Objective 10 Describe the technology used to produce recombinant DNA.

Remarkable technology is available that allows segments of DNA from one organism to be introduced into the genetic material of another organism. The resulting new DNA (containing the foreign segment) is referred to as **recombinant DNA**. The application of this technology, commonly called *genetic engineering*, has produced major advances in human health care and holds the promise for a future of exciting advances in biology, agriculture (see **Figure 21.25**), and many other areas of study.

recombinant DNA DNA of an organism that contains genetic material from another organism.

Don Farrall/Photodisc/Getty Images

FIGURE 21.25 This tomato, a beneficiary of genetic engineering, has an increased shelf life.

An early success of genetic engineering was the introduction of the gene for human insulin into the DNA of the common bacterium *E. coli*. The bacterium then transcribed and translated the information carried by the gene and produced the protein hormone. By culturing such *E. coli*, it has become possible to produce and market large quantities of human insulin. The availability of human insulin is very important for diabetics allergic to the insulin traditionally used, which is isolated from the pancreatic tissue of slaughtered pigs or cattle. **Table 21.4** lists several other medically important materials that have been produced through genetic engineering.

TABLE 21.4 Some Substances Produced by Genetic Engineering

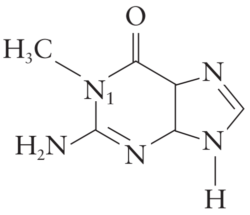
Substance	Use
Human insulin	Treatment of diabetes mellitus
Human growth hormone	Treatment of dwarfism
Interferon	Fights viral infections
Hepatitis B vaccine	Protection against hepatitis
Malaria vaccine	Protection against malaria
Tissue plasminogen activator	Promotes the dissolving of blood clots

21.10A Enzymes Used in Genetic Engineering

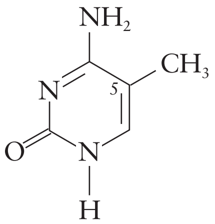
The discovery of restriction enzymes in the 1960s and 1970s made genetic engineering possible. **Restriction enzymes**, which are found in a wide variety of bacterial cells, catalyze the cleaving of DNA molecules. These enzymes are normally part of a mechanism that protects certain bacteria from invasion by foreign DNA, such as that of a virus.

restriction enzyme A protective enzyme found in some bacteria that catalyzes the cleaving of all but a few specific types of DNA.

In these bacteria, some of the bases in their DNA have methyl groups attached. For example, the following compounds are found:



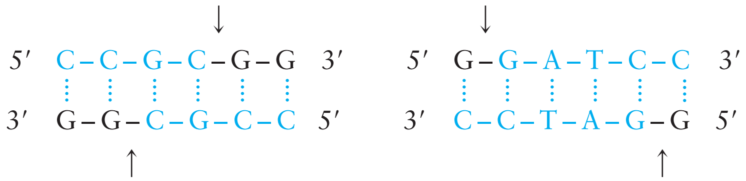
1-methylguanine



5-methylcytosine

The methylated DNA of these bacteria is left untouched by the restriction enzymes, but foreign DNA that lacks the methylated bases undergoes rapid cleavage of both strands and thus becomes nonfunctional. Because there is a "restriction" on the type of DNA allowed in the bacterial cell, the protective enzymes are called restriction enzymes.

Restriction enzymes act at sites on DNA called palindromes. In language, a palindrome is any word or phrase that reads the same in either direction, such as "radar" or "Madam, I'm Adam." For double-stranded DNA, a palindrome is a section in which the two strands have the same sequence but run in opposite directions. Examples of DNA palindromes follow; the arrows indicate the points of attack by restriction enzymes:



HEALTH CONNECTIONS **21.2**

Gene Editing and Your Health

Many diseases are caused by an error (mutation) in our DNA that results in a faulty protein product being produced. Cystic fibrosis is one such disease. Pharmaceutical treatments for cystic fibrosis are designed to treat the effects of the disease, such as drugs that will thin the mucus of the lungs. However, these drugs will never be a cure, since the cause of the disease is a DNA mutation. A true cure would involve editing the DNA so that only normal protein products are made.

Although this idea might seem like science fiction, researchers are excited about the CRISPR-Cas9 system. CRISPR, which stands for clustered regularly interspaced short palindromic repeat, refers to a series of repeating patterns found in the DNA of bacteria. These repeating patterns originated as a primitive immune system for bacteria to recognize invading viruses. RNA transcribed from the repeating patterns will bind to a nucleotide-cutting enzyme called Cas 9. When Cas 9 is combined with a guide RNA, it will bind a complementary invading DNA or RNA sequence and chop it up, thereby preventing invasion.

Although cutting viral DNA or RNA will inactivate it, cutting human DNA results in the activation of DNA repair mechanisms. Because the guide RNA-Cas 9 complex is recruited to certain regions of DNA, it is possible to edit very specific regions of DNA. CRISPR-Cas 9 technology has been used to change a single base of DNA, replace a faulty gene, splice in new genes, and inactivate genes. With this in mind, it might be a logical jump to the conclusion that a cure for cystic fibrosis is around the corner. Among the many challenges, a major one is how to deliver CRISPR-Cas 9 gene-editing technology to every cell. Challenges aside, gene-editing technology is being used in new and inventive ways every day. CRISPR technology has the potential to transform medicine, enabling us to prevent many diseases.

Alexander Heinl/picture alliance/Getty Images

Jennifer Doudna (left), American biochemist, and Emmanuelle Charpentier, French microbiologist, are codiscoverers of the genetic tool CRISPR-Cas9 and cowinners of the 2020 Nobel Prize in Chemistry.

At least 100 bacterial restriction enzymes are known, and each catalyzes DNA cleavage in a specific and predictable way. These enzymes are the tools used to take DNA apart and reduce it to fragments of known size and nucleotide sequence.

Another set of enzymes important in genetic engineering, called DNA ligases, has been known since 1967. These enzymes normally function to connect DNA fragments during replication, and they are used in genetic engineering to put together pieces of DNA produced by restriction enzymes.

21.10B Plasmids

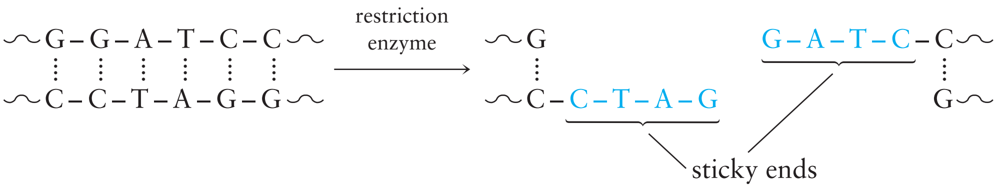
The introduction of a new DNA segment (gene) into a bacterial cell requires the assistance of a DNA carrier called a **vector**. The vector is often a circular piece of double-stranded DNA called a **plasmid**. Plasmids range in size from 2000 to several hundred thousand nucleotides and are found in the cytoplasm of bacterial cells. Plasmids function as accessories to chromosomes by carrying genes for the inactivation of antibiotics and the production of toxins. They have the unusual ability to replicate independently of chromosomal DNA. A typical bacterial cell contains about 20 plasmids and one or two chromosomes.

vector A carrier of foreign DNA into a cell.

plasmid Circular, double-stranded DNA found in the cytoplasm of bacterial cells.

21.10C The Formation of Recombinant DNA

The recombinant DNA technique begins with the isolation of a plasmid from a bacterium. A restriction enzyme is added to the plasmid, which is cleaved at a specific site:


~G–G–A–T–C–C~
~C–C–T–A–G–G~
restriction enzyme
~G
~C–C–T–A–G
G–A–T–C–C~
G~
sticky ends

Because a plasmid is circular, cleaving it this way produces a double-stranded chain with two ends (see **Figure 21.26**). These are called "sticky ends" because each has one

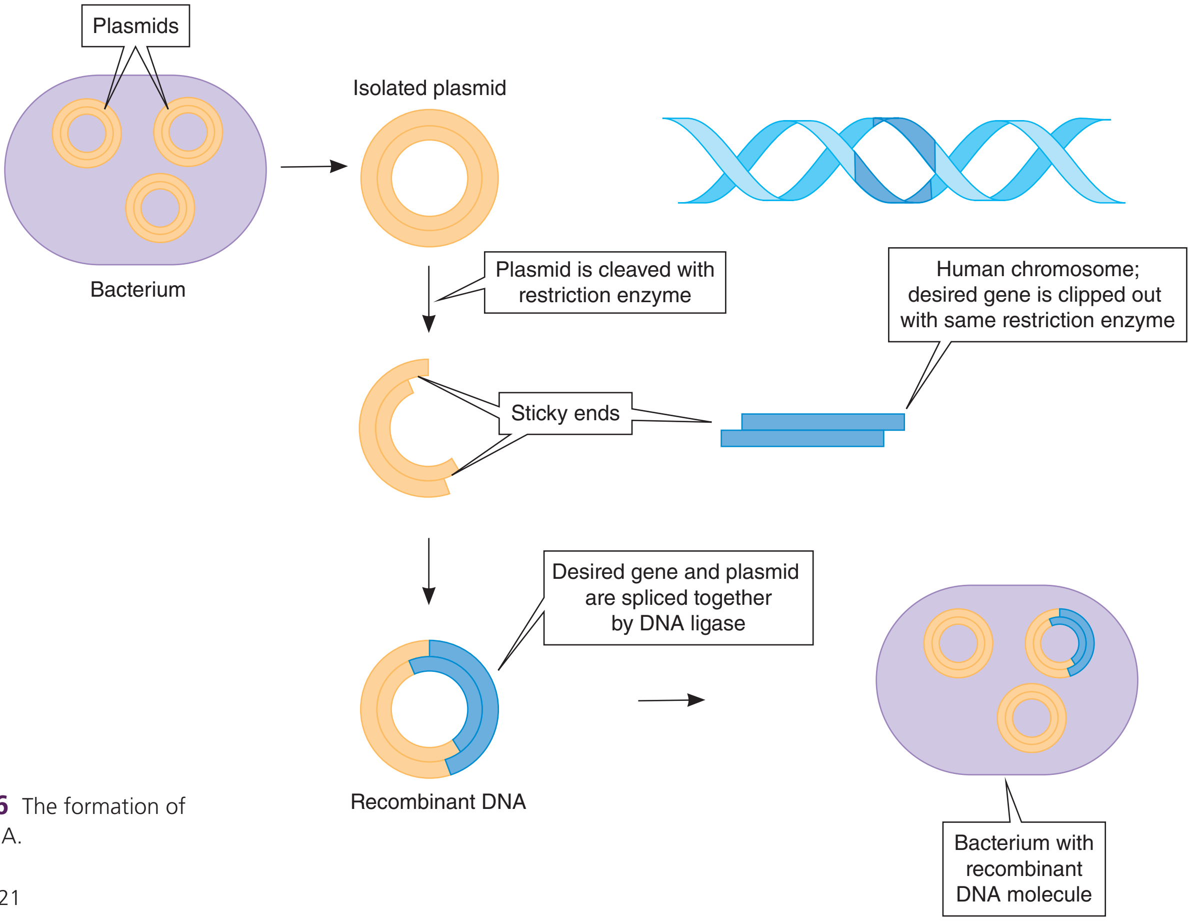
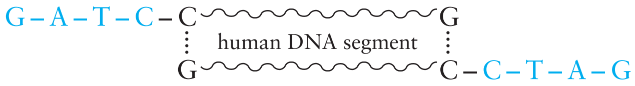

Plasmids
Bacterium
Isolated plasmid
Plasmid is cleaved with restriction enzyme
Human chromosome; desired gene is clipped out with same restriction enzyme
Sticky ends
Desired gene and plasmid are spliced together by DNA ligase
Recombinant DNA
Bacterium with recombinant DNA molecule

FIGURE 21.26 The formation of recombinant DNA.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

strand in which several bases are unpaired and ready to pair up with a complementary section if available.

The next step is to provide the sticky ends with complementary sections for pairing. A human chromosome is cleaved into several fragments using the same restriction enzyme. Because the same enzyme is used, the human DNA is cleaved such that the same sticky ends result:



To splice the human gene into the plasmid, the two are brought together under conditions suitable for the formation of hydrogen bonds between the complementary bases of the sticky ends. The breaks in the strands are then joined by using DNA ligase, and the plasmid once again becomes a circular piece of double-stranded DNA that now incorporates both human and bacterial DNA (see **Figure 21.26**); recombinant DNA has been formed.

Bacterial cells are bathed in a solution containing recombinant DNA plasmids, which diffuse into the cells. When the bacteria reproduce, they replicate all the genes, including the recombinant DNA plasmid. Bacteria multiply quickly, and soon a large number of bacteria, all containing the modified plasmid, are manufacturing the new protein as directed by the recombinant DNA.

The use of this technology makes possible (in principle) the large-scale production of virtually any polypeptide or protein. By remembering the many essential roles these substances play in the body, it is easy to predict that genetic engineering will make tremendous contributions to improving health care in the future.

Environmental Career Description:

AVIAN FIELD TECHNICIAN

Avian field technicians work with birds in a variety of ways under the supervision of research biologists working for government organizations, such as U.S. Fish and Wild Life (USFWS) or U.S. Geological Services (USGS), or licensed private environmental laboratories.

Avian field technicians work "in the field" as their name suggests, but often record and analyze data collected from the field in research laboratories. The bulk of their work is seasonal, during the time that birds are nesting or easily observed.

Physical fitness is a must for avian field technicians in order to hike long distances, often over rugged terrain or through mud in inhospitable weather. They frequently use equipment such as all-terrain vehicles or kayaks to access remote areas in order to find their target species. Field technicians may assist certified researchers in banding birds, collecting blood or tissue samples or inspecting bird nests. They record data in the field, including weather data, such as air temperature, humidity, and wind speed, along with observations of bird behavior and nesting conditions.

Avian technicians are expected to recognize bird species by sight and call. They are expected to use optical equipment such as spotting scopes and binoculars with expertise. In addition to studying birds, they may work with vegetation that provides habitat for the birds they study.

A Colorado Department of Wildlife job posting lists the following in an avian field technician posting: "Technicians must be able to identify all bird species found in Colorado by sight and sound upon completion of training, and should expect to hike long distances off-trail in steep and rugged terrain on a regular basis. Primitive camping, often without phone service or facilities, and some overnight backcountry travel to survey remote road-less areas will be required. Completion of job duties will require long days in the field."

Avian field technician is an excellent career choice for outdoor enthusiasts interested in pursuing an associate degree or higher in biology.

Sources: Avian Ecology Laboratory. (n.d.). Weber State University. Retrieved Apr. 26, 2020 from http://departments.weber.edu/avianecologylab/index.htm; Texas A&M Job Board. Department of Wildlife and Fisheries Sciences Job Board. (n.d.) Avian Field Technician Colorado. Retrieved Apr. 26, 2020 from https://wfscjobs.tamu.edu/jobs/avian-field-technician-colorado/

Concept Summary

21.1 Components of Nucleic Acids

Learning Objective: Can you identify the components of nucleotides and correctly classify the sugars and bases?

- Nucleic acids are classified into two categories: ribonucleic acids (RNA) and deoxyribonucleic acids (DNA).
- Both types are polymers made up of monomers called nucleotides.
- All nucleotides are composed of a pyrimidine or purine base, a sugar, and phosphate.
- The sugar component of RNA is ribose and that of DNA is deoxyribose.
- The bases adenine, guanine, and cytosine are found in all nucleic acids.
- Uracil is found only in RNA.
- Thymine is found only in DNA.

21.2 The Structure of DNA

Learning Objective: Can you describe the structure of DNA?

- The nucleotides of DNA are joined by linkages between phosphate groups and sugars.
- The resulting sugar–phosphate backbone is the same for all DNA molecules, but the order of attached bases along the backbone varies.
- This order of nucleotides with attached bases is the primary structure of nucleic acids.
- The secondary structure is a double-stranded helix held together by hydrogen bonds between complementary base pairs on the strands.

21.3 DNA Replication

Learning Objective: Can you outline the process of DNA replication?

- The replication of DNA occurs when a double strand of DNA unwinds at specific points.
- The exposed bases match up with complementary bases of nucleotides.
- The nucleotides bind together to form two new strands that are complementary to the strands that separated.
- Thus, the two new DNA molecules each contain one old strand and one new strand.

21.4 Ribonucleic Acid (RNA)

Learning Objective: Can you contrast the structures of DNA and RNA and list the function of the three main types of cellular RNA?

- Three main forms of ribonucleic acid are found in cells:
  - messenger RNA
  - ribosomal RNA
  - transfer RNA.
- Each form serves an important function during protein synthesis.
- All RNA molecules are single-stranded, but some contain loops or folds.

21.5 The Flow of Genetic Information

Learning Objective: Can you describe what is meant by the terms *transcription and translation*?

- The flow of genetic information occurs in two steps called transcription and translation.
- In transcription, information stored in DNA molecules is passed to molecules of messenger RNA.
- In translation, the messenger RNA serves as a template that directs the assembly of amino acids into proteins.

21.6 Transcription: RNA Synthesis

Learning Objective: Can you describe the process by which RNA is synthesized in cells?

- The various RNAs are synthesized in much the same way as DNA is replicated.
- Nucleotides with complementary bases align themselves against one strand of a partially unwound DNA segment that contains the genetic information that is to be transcribed.
- The aligned nucleotides bond together to form the RNA.
- In eukaryotic cells, the produced RNA is heterogeneous and is cut and spliced after being synthesized to produce the functional RNA.

21.7 The Genetic Code

Learning Objective: Can you explain how the genetic code functions in the flow of genetic information?

- The genetic code is a series of three-letter words that represent the amino acids of proteins as well as start and stop signals for protein synthesis.
- The letters of the words are the bases found on mRNA, and the words on mRNA are called codons.
- The genetic code is the same for all organisms and is degenerate for most amino acids.

21.8 Translation and Protein Synthesis

Learning Objective: Can you outline the process by which proteins are synthesized in cells?

- The translation step in the flow of genetic information results in the synthesis of proteins.
- The synthesis takes place when properly coded mRNA forms a complex with the component of a ribosome.
- Transfer RNA molecules carrying amino acids align themselves along the mRNA in an order representing the correct primary structure of the protein.
- The order is determined by the matching of complementary codons on the mRNA to anticodons on the tRNA.
- The amino acids sequentially bond together to form the protein, which then spontaneously forms characteristic secondary and tertiary structures.

21.9 Mutations

Learning Objective: Can you describe how genetic mutations occur and how they influence organisms?

- Any change that results in an incorrect sequence of bases on DNA is called a mutation.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

- Some mutations occur naturally during DNA replication, whereas others are induced by environmental factors.
- Some mutations are beneficial to organisms.
- Others may be lethal or result in genetic diseases.

21.10 Recombinant DNA

Learning Objective: Can you describe the technology used to produce recombinant DNA?

- The discovery and application of restriction enzymes and DNA ligases have resulted in a technology called genetic engineering.
- The primary activities of genetic engineers are the isolation of genes (DNA) that code for specific useful proteins and the introduction of these genes into the DNA of bacteria.
- The new (recombinant) DNA in the rapidly reproducing bacteria mediates production of the useful protein, which is then isolated for use.

Key Terms and Concepts

Anticodon (21.4)
Central dogma of molecular biology (21.5)
Chromosome (21.3)
Codon (21.7)
Complementary DNA strands (21.2)
Deoxyribonucleic acid (DNA) (21.1)
Exon (21.6)
Gene (21.3)
Heterogeneous nuclear RNA (hnRNA) (21.6)
Intron (21.6)
Messenger RNA (mRNA) (21.4)
Mutagen (21.9)
Mutation (21.9)
Nucleic acid (Introduction)
Nucleic acid backbone (21.2)
Nucleotide (21.1)
Okazaki fragment (21.3)
Plasmid (21.10)
Polyribosome (polysome) (21.8)
Recombinant DNA (21.10)
Replication (21.3)
Replication fork (21.3)
Restriction enzyme (21.10)
Ribonucleic acid (RNA) (21.1)
Ribosomal RNA (rRNA) (21.4)
Ribosome (21.4)
Semiconservative replication (21.3)
Transcription (21.5)
Transfer RNA (tRNA) (21.4)
Translation (21.5)
Vector (21.10)

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Components of Nucleic Acids (Section 21.1)

21.1 What is the principal location of DNA within the eukaryotic cell?

21.2 Which pentose sugar is present in DNA? In RNA?

21.3 Name the three components of nucleotides.

21.4 Indicate whether each of the following is a pyrimidine or a purine:

- **a.** guanine
- **b.** thymine
- **c.** uracil
- **d.** cytosine
- **e.** adenine

21.5 Which bases are found in DNA? In RNA?

21.6 List the different choices there are for each of the following subunits in the given type of nucleotide.

- **a.** Pentose sugar subunit in DNA nucleotides
- **b.** Base subunit in RNA nucleotides
- **c.** Phosphate subunit in RNA nucleotides

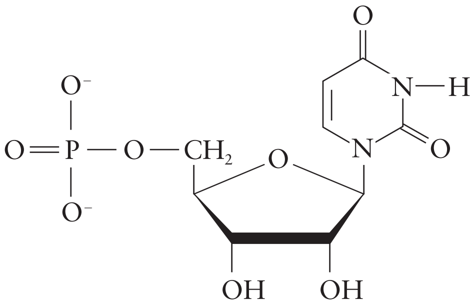
21.7 List the different choices there are for each of the following subunits in the given type of nucleotide.

- **a.** Pentose sugar subunit in RNA nucleotides
- **b.** Base subunit in DNA nucleotides
- **c.** Phosphate subunit in DNA nucleotides

21.8 Write the structural formula for the nucleotide thymidine 5′-monophosphate. The base component is thymine.

21.9 Write the structural formula for the nucleotide guanosine 5′-monophosphate. The base component is guanine; the sugar is ribose.

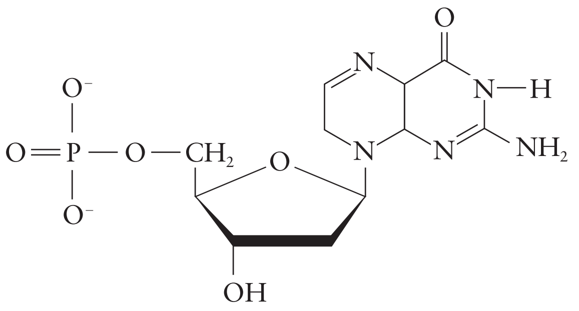
21.10 Identify each of the following statements about the nucleotide below as true or false.



- **a.** The base is a purine derivative.
- **b.** The phosphate group is attached to the sugar unit at carbon 3′.
- **c.** The sugar unit is ribose.
- **d.** The nucleotide can only be a component of DNA.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

21.11 Identify each of the following statements about the nucleotide below as true or false.



a. The sugar unit is deoxyribose.

b. The sugar unit is attached to the base unit at carbon 1′.

c. The base is a pyrimidine derivative.

d. The nucleotide could be a component of both DNA and RNA.

The Structure of DNA (Section 21.2)

21.12 In what way might two DNA molecules that contain the same number of nucleotides differ?

21.13 Identify the 3′ and 5′ ends of the DNA segment AGTCAT.

21.14 What data obtained from the chemical analysis of DNA supported the idea of complementary base pairing in DNA proposed by Watson and Crick?

21.15 Describe the secondary structure of DNA as proposed by Watson and Crick.

21.16 Describe the role of hydrogen bonding in the secondary structure of DNA.

21.17 How many total hydrogen bonds would exist between the following strands of DNA and their complementary strands?

a. CAGTAG

b. TTGACA

21.18 How many total hydrogen bonds would exist between the following strands of DNA and their complementary strands?

a. GCATGC

b. TATGGC

21.19 Of the two DNA strands in Exercise 21.17, determine which strand of DNA and its complementary strand would require the most energy to break apart. Explain your answer.

21.20 Of the two DNA strands in Exercise 21.18, determine which strand of DNA and its complementary strand would require the most energy to break apart. Explain your answer.

21.21 The base content of a particular double-stranded DNA segment is 43% adenine. What is the percentage of each of the following bases in the DNA segment?

a. Thymine

b. Guanine

c. Cytosine

21.22 The base content of a particular double-stranded DNA segment is 36% cytosine. What is the percentage of each of the following bases in the DNA segment?

a. Adenine

b. Guanine

c. Thymine

21.23 A strand of DNA has the base sequence ATGCATC. Write the base sequence for the complementary strand.

21.24 A strand of DNA has the base sequence GATTCA. Write the base sequence for the complementary strand.

21.25 A single strand of DNA has the base composition of 19% A, 34% C, 28% G, and 19% T. What is the percent base composition for the complementary DNA strand?

21.26 A single strand of DNA has the base composition of 21% A, 29% C, 36% G, and 14% T. What is the percent base composition for the complementary DNA strand?

DNA Replication (Section 21.3)

21.27 What is a chromosome? How many chromosomes are in a human cell? What is the approximate number of genes in a human cell?

21.28 What is meant by the term *semiconservative replication*?

21.29 What is a replication fork?

21.30 Describe the function of the enzyme helicase in the replication of DNA.

21.31 List the steps involved in DNA replication.

21.32 What enzymes are involved in DNA replication?

21.33 In what direction is a new DNA strand formed?

21.34 Explain how the synthesis of a DNA daughter strand growing toward a replication fork differs from the synthesis of a daughter strand growing away from a replication fork.

21.35 The base sequence ACGTCT represents a portion of a single strand of DNA. Draw the complete double-stranded molecule for this portion of the strand and use the representation to illustrate the replication of the DNA strand. Be sure to clearly identify the nucleotide bases involved, the new strands formed, and the daughter DNA molecules.

21.36 The base sequence GTACGT represents a portion of a single strand of DNA. Draw the complete double-stranded molecule for this portion of the strand and use the representation to illustrate the replication of the DNA strand. Be sure to clearly identify the nucleotide bases involved, the new strands formed, and the daughter DNA molecules.

21.37 Explain the origin of Okazaki fragments.

21.38 Two daughter molecules, Q and R, are formed in the replication of a DNA molecule. The base sequence below is part of the newly formed daughter molecule Q:

5′ AACTGG 3′

With this information, write the base sequence (5′→3′) for each of the following:

a. The newly formed strand in daughter molecule R

b. The "parent" strand for daughter molecule Q

c. The "parent" strand for daughter molecule R

21.39 Two daughter molecules, S and T, are formed in the replication of a DNA molecule. The base sequence below is part of the newly formed daughter molecule T:

5′ ACGTAT 3′

With this information, write the base sequence (5′→3′) for each of the following:

a. The newly formed strand in daughter molecule T

b. The "parent" strand for daughter molecule S

c. The "parent" strand for daughter molecule T

21.40 DNA ligase closes nicks between Okazaki fragments during DNA replication. Below are three proposed mechanisms for how the enzyme works. Identify the correct mechanism of ligase function. Explain your choice.

a. Ligase adds a base unit to the deoxyribose sugar unit carbon 1′, thereby closing the nick.

b. Ligase adds new base units to the 3′ end of the newly replicated Okazaki fragment.

c. Ligase forms a phosphodiester bond between the 5′ phosphate of one Okazaki fragment and the 3′ OH of the deoxyribose sugar on the next Okazaki fragment, thereby closing the nick.

Ribonucleic Acid (RNA) (Section 21.4)

21.41 How does the sugar–phosphate backbone of RNA differ from the backbone of DNA?

21.42 Compare the secondary structures of RNA and DNA.

21.43 Briefly describe the characteristics and functions of the three types of cellular RNA.

21.44 Identify whether each of the following describes mRNA, rRNA, or tRNA.

a. Associated with a series of proteins in a complex structure

b. Contains genetic information needed for protein synthesis

c. Smallest of the RNA molecules

21.45 Identify whether each of the following describes mRNA, rRNA, or tRNA.

a. Delivers amino acids to protein synthesis sites

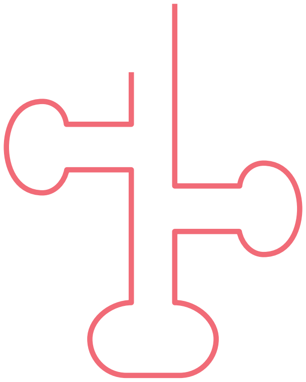
b. Most abundant type of RNA in a cell

c. Usually has a molecular lifetime of less than 1 hour

21.46 Must the ratio of guanine to cytosine be 1:1 in RNA? Explain.

21.47 What are the two important regions of a tRNA molecule?

21.48



Use arrows and label the following on the two-dimensional representation of a tRNA molecule above.

a. The 3′ end and 5′ end of the tRNA molecule

b. The anticodon on the tRNA molecule

c. Helical areas caused by hydrogen bonding between complementary bases along the tRNA molecule

d. Areas where no hydrogen bonding occurs between bases along the tRNA molecule

The Flow of Genetic Information (Section 21.5)

21.49 What is the central dogma of molecular biology?

21.50 In the flow of genetic information, what is meant by the terms *transcription* and *translation*?

Transcription: RNA Synthesis (Section 21.6)

21.51 Briefly describe the synthesis of mRNA in the transcription process.

21.52 Write the base sequence for the mRNA that would be formed during transcription from the DNA strand with the base sequence GCCATATTG.

21.53 Write the base sequence for the hnRNA that would be formed during transcription from the DNA strand with the base sequence ATTGACTCG.

21.54 Write the base sequence for the DNA that coded for the RNA strand with the base sequence UUGCGAAUC.

21.55 Write the base sequence for the DNA that coded for the RNA strand with the base sequence AUGCGUACG.

21.56 Write the base sequence for the mRNA, not hnRNA, formed from the following portion of a gene (DNA).

intron	exon	intron
TCAG	TACG	TTCA

21.57 Write the base sequence for the mRNA, not hnRNA, formed from the following portion of a gene (DNA).

exon	intron	exon
TTAC	AACG	GCAT

21.58* Describe the differences in the transcription and translation processes as they occur in prokaryotic cells and eukaryotic cells.

21.59 What is the relationship among exons, introns, and hnRNA?

The Genetic Code (Section 21.7)

21.60 What is a codon?

21.61 For each of the following mRNA codons, give the tRNA anticodon and use **Table 21.2** to determine the amino acid being coded for by the codon.

a. UAU

b. CAU

c. UCA

d. UCU

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

21.62 For each of the following mRNA codons, give the tRNA anticodon and use **Table 21.2** to determine the amino acid being coded for by the codon.

a. GUA

b. CCC

c. CAC

d. CCA

21.63 Write the sequence of amino acids coded for by the following mRNA sequence:

UGA-GAC-CUA-GGA-GGC

21.64 Write the sequence of amino acids coded for by the following mRNA sequence:

GAA-GAC-CUA-GGA-GGC

21.65 Explain why the base sequence ATC cannot be a codon.

21.66 Explain why the base sequence AGAC cannot be a codon.

21.67 Describe the experiment that allowed researchers to first identify the codon for a specific amino acid.

21.68 Which of the following statements about the genetic code are true and which are false? Correct each false statement.

a. Each codon is composed of four bases.

b. Some amino acids are represented by more than one codon.

c. All codons represent an amino acid.

d. Each living species is thought to have its own unique genetic code.

e. The codon AUG at the beginning of a sequence is a signal for protein synthesis to begin at that codon.

f. It is not known if the code contains stop signals for protein synthesis.

Translation and Protein Synthesis (Section 21.8)

21.69 The β-chain of hemoglobin is a protein that contains 146 amino acid residues. What minimum number of nucleotides must be present in a strand of mRNA that is coded for this protein?

21.70 What is a polysome?

21.71 Beginning with DNA, describe in simple terms (no specific codons, etc.) how proteins are coded and synthesized.

21.72 List the three major stages in protein synthesis.

21.73 Does protein synthesis begin with the N-terminal or with the C-terminal amino acid?

21.74 What is meant by the terms *A site* and *P site*?

21.75* Beginning with DNA, describe specifically the coding and synthesis of the following tetrapeptide that represents the first four amino acid residues of the hormone oxytocin: Gly–Leu–Pro–Cys. Be sure to include processes such as formation of mRNA (use correct codons, etc.), attachment of mRNA to a ribosome, attachment of tRNA to mRNA-ribosome complex, and so on.

Mutations (Section 21.9)

21.76 What is a genetic mutation?

21.77 Briefly explain how genetic mutations can do the following:

a. Harm an organism

b. Help an organism

21.78 What is the result of a genetic mutation that causes the mRNA sequence GCC to be replaced by CCC?

21.79 Write the amino acid sequence made in each of the following ways for the codon sequence GGC-UAU-AGU-AGA.

a. Translation proceeds in a normal manner.

b. A mutation changes AGA to AGG.

c. A mutation changes AGA to AUA.

21.80 Write the amino acid sequence made in each of the following ways for the codon sequence UCG-GGA-AUA-UGG

a. Translation proceeds in a normal manner.

b. A mutation changes UCG to ACG.

c. A mutation changes UCG to UCU.

Recombinant DNA (Section 21.10)

21.81 Explain the function and importance of restriction enzymes and DNA ligase in the formation of recombinant DNA.

21.82 Explain how recombinant DNA differs from normal DNA.

21.83 Explain what plasmids are and how they are used to get bacteria to synthesize a new protein that they normally do not synthesize.

21.84 List three substances likely to be produced on a large scale by genetic engineering, and give an important use for each.

Additional Exercises

21.85 Explain how heating a double-stranded DNA fragment to 94°C–96°C when performing PCR causes the DNA to unravel into single strands.

21.86 Review **Figure 21.5** and suggest a reaction that would be used to excise introns from hnRNA. Also suggest a reaction that would be used to join the exon segments together.

21.87 A segment of DNA has an original code of –ACA–. This segment was mutated to –AAA–. After the mutation occurred, the protein that was coded for was no longer able to maintain its tertiary structure. Explain why.

21.88 A species of bacteria can use sucrose as its sole source of carbon energy. The bacterial enzyme Q is used to hydrolyze sucrose into its constituent monosaccharides. In the absence of sucrose, there are fewer than 10 enzyme Q molecules in a bacterial cell. In the presence of sucrose there are more than several thousand enzyme molecules in a single cell. Enzyme Q does not exist as a zymogen.

a. What are the constituent monosaccharides of sucrose?

b. What is the specific type of enzyme regulation that controls enzyme Q?

c. Suggest a mechanism of how this type of enzyme regulation occurs.

21.89 During DNA replication, about 1000 nucleotides are added per minute per molecule of DNA polymerase. The genetic material in a single human cell consists of about 3 billion nucleotides.

a. How many years would it take one DNA polymerase enzyme to replicate the genetic material in one cell?

b. How many DNA polymerase molecules would be needed to replicate a cell's genetic material in 10 minutes (assuming equidistance between replication forks)?

Chemistry for Thought

21.90 Genetic engineering shows great promise for the future but has been controversial at times. Discuss with some classmates the pros and cons of genetic engineering. List two benefits and two concerns that come from your discussion.

21.91 Two samples of DNA are compared, and one has a greater percentage of guanine-cytosine base pairs. How should that greater percentage affect the attractive forces holding the double helix together?

21.92 If DNA replication were not semiconservative, what might be another possible structure for the daughter DNA molecules?

21.93 The genetic code contains three stop signals and 61 codons that code for 20 amino acids. From the standpoint of mutations, why are we fortunate that the genetic code does not have only the required 20 amino acid codons and 44 stop signals?

21.94 Azidothymidine (AZT), a drug used to fight HIV, is believed to act as an enzyme inhibitor. What type of enzyme inhibition is most likely caused by this drug?

21.95 If DNA specifies only the primary structure of a protein, how does the correct three-dimensional protein structure develop?

21.96 When were the first experiments carried out that produced genetically modified plants?

21.97 How does the DNA content determine what reactions occur within an organism?

21.98 What would be the ramifications if DNA were single stranded?

22 Nutrition and Energy for Life

Pixel-Shot/Shutterstock.com

Health Career Focus

NUTRITIONIST/NUTRITION THERAPIST

My doctor suggested I see a nutrition therapist to help manage my irritable bowel syndrome (IBS). Medications helped, but IBS still made daily life difficult. It's one thing for a doctor to tell you to eat correctly, but sometimes you need more help.

My nutrition therapist explained that the practice was not about weight loss, but about learning how to respect and care for my body. The therapist said that accurate measurements and records were key to treatment. I took home a digital food scale and a notebook. The therapist wanted me to weigh everything I ate and record it in the notebook.

My therapist conducted a full interview about my medical, social, and emotional history, recorded my weight, and calculated my body composition with a skin-fold test using calipers. I felt confident that with the therapist's help, I could finally make some healthy changes.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Describe the difference between macronutrients and micronutrients in terms of amounts required and their functions in the body. **(Section 22.1)**
2. Describe the primary functions in the body of each macronutrient. **(Section 22.2)**
3. Distinguish between and classify vitamins as water-soluble or fat-soluble on the basis of name and behavior in the body. **(Section 22.3)**
4. List a primary function in the body for each major mineral. **(Section 22.4)**
5. Describe the major steps in the flow of energy in the biosphere. **(Section 22.5)**
6. Differentiate among metabolism, anabolism, and catabolism. **(Section 22.6)**
7. Outline the three stages in the extraction of energy from food. **(Section 22.6)**
8. Explain how ATP plays a central role in the production and use of cellular energy. **(Section 22.7)**
9. Explain the role of coenzymes in the common catabolic pathway. **(Section 22.8)**

THE SCIENCE OF nutrition is an applied field that focuses on the study of food, water, and other nutrients and the ways in which living organisms utilize them. Nutrition scientists use the principles of nutrition to obtain answers to questions that have a great deal of practical significance. For example, they might try to determine the proper components of a sound diet, the best way to maintain proper body weight, or the foods and other nutrients needed by people with specific illnesses or injuries.

The fuels of the human body are the sugars, lipids, and proteins derived from food (see **Figure 22.1**). The reactions that release energy from these substances are among the body's most important biochemical processes. In this chapter, we will study an introduction to nutrition and how cells extract energy from food.

nutrition An applied science that studies food, water, and other nutrients and the ways living organisms use them.

© Michael C. Slabaugh

FIGURE 22.1 Carbohydrates, lipids, and proteins from food supply the energy for all of our activities.

22.1 Nutritional Requirements

Learning Objective 1 Describe the difference between macronutrients and micronutrients in terms of amounts required and their functions in the body.

A human body must be supplied with appropriate nutrients if it is to function properly and remain healthy. Some nutrients are required in relatively large amounts (gram quantities daily) because they provide energy and materials required to repair damaged tissue or build new tissue. These **macronutrients** are the carbohydrates, lipids, and proteins contained in food. **Micronutrients** are required by the body in only small amounts (milligrams or micrograms daily). The small quantities needed suggest correctly that at least some micronutrients are utilized in enzymes. Micronutrients are classified as either vitamins or minerals.

macronutrient A substance needed by the body in relatively large amounts.

micronutrient A substance needed by the body only in small amounts.

In addition to macronutrients and micronutrients, the human body must receive appropriate amounts of water and fiber. The importance of water becomes obvious when we learn that 45–75% of the human body mass is water. Fiber is an indigestible plant material composed primarily of cellulose. Fiber makes no contribution to the body in the form of macronutrients or micronutrients, but it prevents or relieves constipation by absorbing water and softening the stool for easier elimination.

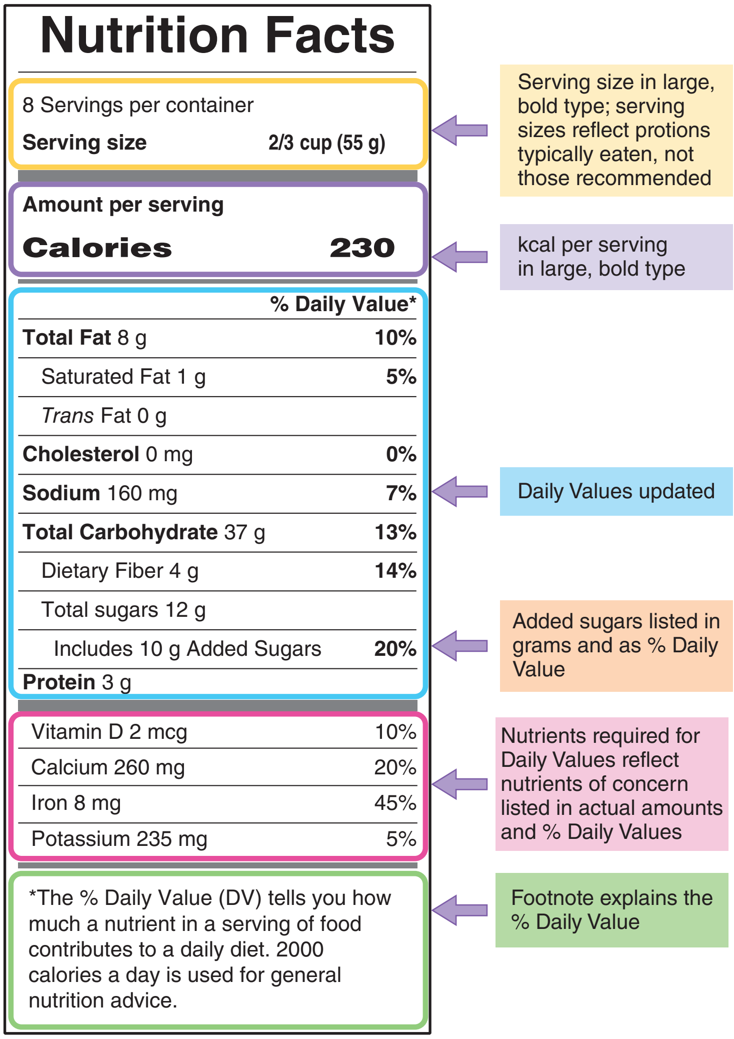
A number of countries of the world have established nutritional guidelines for their citizens in an attempt to improve and maintain good health nationally. In the United States, the Nutrition Labeling and Education Act of 1990 brought sweeping changes to the regulations that define what is required on a food label. The official guidelines are called **Reference Daily Intakes (RDIs)** for proteins and 19 vitamins and minerals, and **Daily Reference Values (DRVs)** for other nutrients of public health importance. For simplicity, all reference values on food labels are referred to as **Daily Values (DVs)** (see **Figure 22.2**). In 2016, the Food and Drug Administration (FDA) finalized the new Nutrition Facts label for packaged foods. The new label makes it easier for consumers to make better informed food choices. The FDA decided to use 2000 calories as a standard for energy intake in calculating the DRVs.

Reference Daily Intakes (RDIs) A set of standards for protein, vitamins, and minerals used on food labels as part of the Daily Values.

Daily Reference Values (DRVs) A set of standards for nutrients and food components (such as fat and fiber) that have important relationships with health; used on food labels as part of the Daily Values.

Daily Values (DVs) Reference values developed by the FDA specifically for use on food labels. The Daily Values represent two sets of standards: Reference Daily Intakes (RDIs) and Daily Reference Values (DRVs).

A 2000-calorie diet is considered about right for many adults. Recall from **Chapter 1** that the nutritional calorie is equal to 1 kilocalorie (kcal) of energy. The guidelines are reviewed and revised about every 5 years. The U.S. Department of Agriculture (USDA) has issued the food guide MyPlate, designed to replace the old MyPyramid posters with new recommendations (see **Figure 22.3**).



Nutrition Facts

8 Servings per container

Serving size	**2/3 cup (55 g)**
Amount per serving	
Calories	**230**
	% Daily Value*
Total Fat 8 g	**10%**
Saturated Fat 1 g	**5%**
Trans Fat 0 g	
Cholesterol 0 mg	**0%**
Sodium 160 mg	**7%**
Total Carbohydrate 37 g	**13%**
Dietary Fiber 4 g	**14%**
Total sugars 12 g	
Includes 10 g Added Sugars	**20%**
Protein 3 g	
Vitamin D 2 mcg	10%
Calcium 260 mg	20%
Iron 8 mg	45%
Potassium 235 mg	5%

*The % Daily Value (DV) tells you how much a nutrient in a serving of food contributes to a daily diet. 2000 calories a day is used for general nutrition advice.

Serving size in large, bold type; serving sizes reflect protions typically eaten, not those recommended

kcal per serving in large, bold type

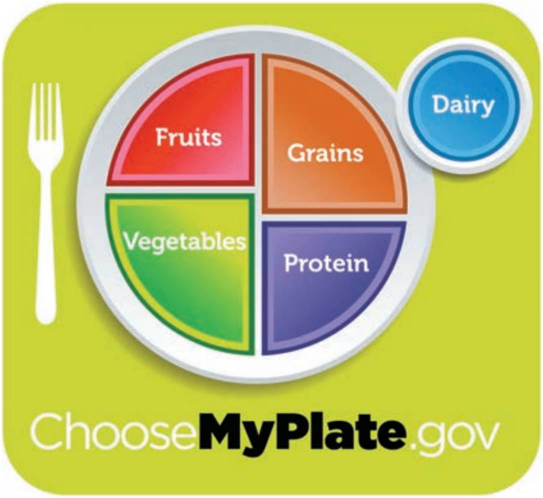
Daily Values updated

Added sugars listed in grams and as % Daily Value

Nutrients required for Daily Values reflect nutrients of concern listed in actual amounts and % Daily Values

Footnote explains the % Daily Value

FIGURE 22.2 An example of a food label.



United States Department of Agriculture

FIGURE 22.3 The food guide MyPlate developed by the U.S. Department of Agriculture. ChooseMyPlate.gov will help you select foods and amounts that are right for you.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

22.2 The Macronutrients

Learning Objective 2 Describe the primary functions in the body of each macronutrient.

22.2A Carbohydrates

Carbohydrates are ideal energy sources for most bodily functions and also provide useful materials for the synthesis of cell and tissue components. These facts, plus the relatively low cost and ready availability of carbohydrates, have led to their worldwide use as the main dietary source of energy.

Despite their importance as a dominant source of energy, many people consider foods rich in carbohydrates to be inferior, at least in part because of their reputation for being fattening. It is now recognized that this reputation is generally not deserved. Most of the excess calories associated with eating carbohydrates are actually due to the high-calorie foods eaten *with* the carbohydrates—for example, potatoes and bread are often eaten with butter, a high-energy lipid.

Dietary carbohydrates are often classified as simple or complex. **Simple carbohydrates** are the sugars we classified earlier as monosaccharides and disaccharides (see **Chapter 17**). **Complex carbohydrates** consist essentially of the polysaccharides amylose and amylopectin, which are collectively called starch. Cellulose, another polysaccharide, is also a complex carbohydrate; however, because it cannot be digested by humans, it serves a nonnutritive role as fiber.

simple carbohydrates Monosaccharides and disaccharides, commonly called sugars.

complex carbohydrates The polysaccharides amylose and amylopectin, collectively called starch.

Numerous nutritional studies include recommendations about dietary carbohydrates in their reports. One conclusion common to most of these studies is that a typical American diet does not include enough complex carbohydrates. These studies recommend that about 58% of daily calories should come from carbohydrate foods. Currently, only about 46% of the typical diet comes from carbohydrates, and too much of that total comes from simple carbohydrates (see **Figure 22.4**). The 2015–2020 Dietary Guidelines

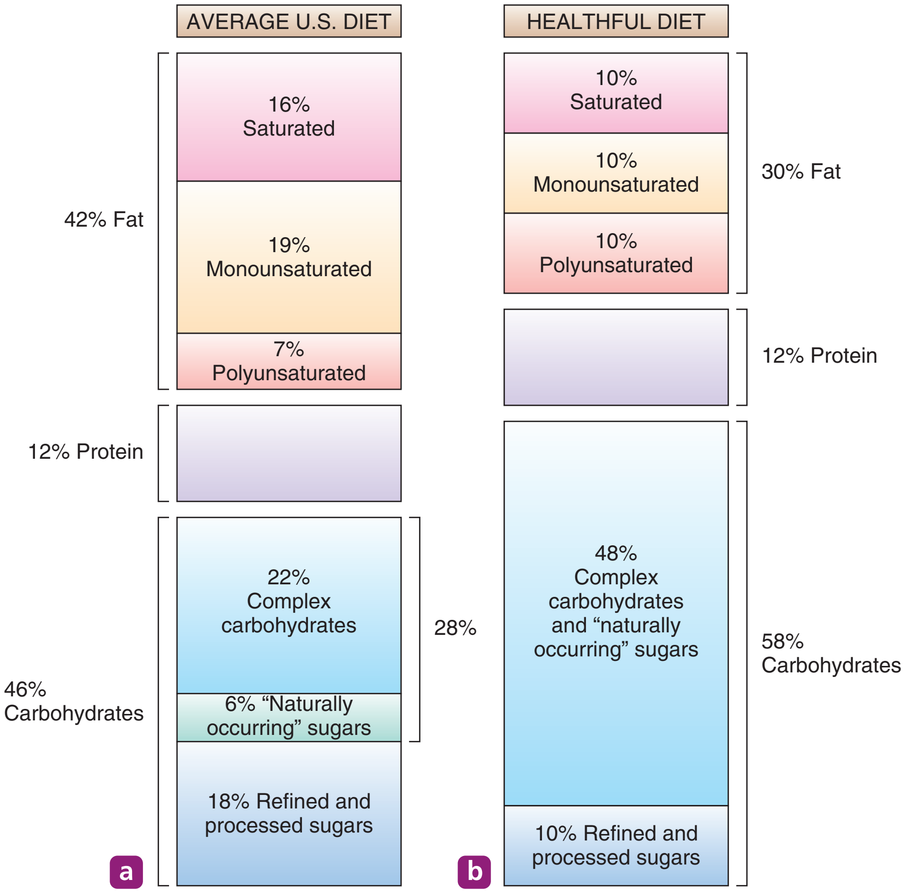


FIGURE 22.4 (**a**) The composition of a typical American diet; (**b**) the composition of a healthful diet with lower fat intake and reduced levels of fat.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

issued by the U.S. Department of Health and Human Services (HHS) and the USDA recommends the consumption of less than 10% of calories per day from added sugars.

Monkey Business Images/Shutterstock.com

FIGURE 22.5 Oil-fried foods are rich in triglycerides.

22.2B Lipids

Lipids, or fats, like carbohydrates, have a somewhat negative dietary image. In part, this is because the word *fat* has several meanings, and its relationship to health is sometimes misunderstood. In our modern society, some people think of fat as something to be avoided at all costs, regardless of body size.

As we saw in **Chapter 18**, a number of different substances are classified as lipids. However, about 95% of the lipids in foods and in our bodies are triglycerides, in which three fatty acid molecules are bonded to a molecule of glycerol by ester linkages. The fatty acids in triglycerides can be either saturated or unsaturated. Generally, triglycerides containing a high percentage of unsaturated fatty acids are liquids at room temperature and are called oils (see **Figure 22.5**). A higher concentration of saturated fatty acids causes triglyceride melting points to increase, and they are solids (fats) at room temperature.

Lipids are important dietary constituents for a number of reasons: They are a concentrated source of energy and provide more than twice the energy of an equal mass of carbohydrate; they contain some fat-soluble vitamins and help carry them through the body; and some fatty acids needed by the body cannot be synthesized and must come from the diet—they are the essential fatty acids.

In addition to metabolic needs, dietary lipids are desirable for other reasons. Lipids improve the texture of foods, and absorb and retain flavors, thus making foods more palatable. Lipids are digested more slowly than other foods and therefore prolong **satiety**, a feeling of satisfaction and fullness after a meal.

satiety A state of satisfaction or fullness.

The essential fatty acids are the polyunsaturated linoleic and linolenic acids. Generally, vegetable oils are good sources of unsaturated fatty acids (see **Figure 22.6**). Some oils that

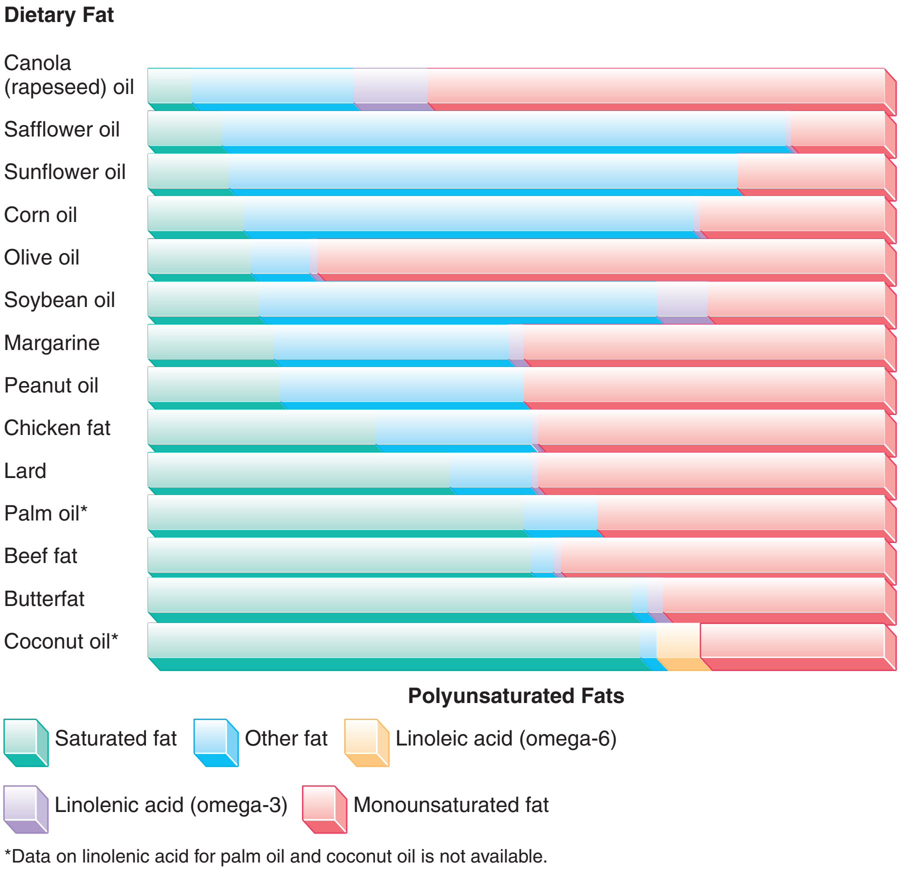


FIGURE 22.6 The fatty acid composition of common food fats.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

are especially rich in linoleic acid come from corn, cottonseed, soybean, and wheat germ. Infants especially need linoleic acid for good health and growth; human breast milk contains a higher percentage of it than does cow's milk.

We still do not have a complete understanding of the relationship between dietary lipids and health. A moderate amount of fat is needed in everyone's diet, but many people consume much more than required. Research results indicate a correlation between the consumption of too much fat, and fat of the wrong type (saturated fatty acids), and two of the greatest health problems: obesity and cardiovascular disease. Because of these results, there is a recommended reduction in the percentage of calories obtained from fats—from the national average of almost 42% to no more than 30%. The 2015–2020 Dietary Guidelines issued by the HHS and the USDA recommends the consumption of less than 10% of calories per day from saturated fats.

22.2C Proteins

Proteins are the only macronutrients for which a Reference Daily Intake (RDI) has been established. The RDI varies for different groups of people, as shown in **Table 22.1**, which shows that nursing mothers have a greater need for protein than do other adults. This reflects one of the important uses of protein in the body, the production of new tissue as the body grows. In addition, proteins are needed for the maintenance and repair of cells and for the production of enzymes, hormones, and other important nitrogen-containing compounds of the body. Proteins can also be used to supply energy; they provide about 4 calories/gram, the same as carbohydrates. It is recommended that 12% of the calories obtained from food be obtained from dietary proteins (see **Figure 22.4**).

TABLE 22.1 The RDI for Protein

Group	RDI (g)
Pregnant women	60
Nursing mothers	65
Infants under age 1	14
Children age 1 to 4	16
Adults	50

As we learned in **Chapter 19**, proteins are natural polymers of amino acids joined by amide (or peptide) linkages. On digestion, proteins are broken down to individual amino acids that are absorbed into the body's amino acid pool and used for the purposes mentioned earlier. The **essential amino acids** listed in **Table 22.2** must be obtained from the diet because they cannot be synthesized in the body in sufficient amounts to satisfy the body's needs.

essential amino acid An amino acid that cannot be synthesized within the body at a rate adequate to meet metabolic needs.

The minimum quantity of each essential amino acid needed per day by an individual will vary, depending on the use in the body. For example, results of one study showed that young men need a daily average of only 7 g (0.034 mol) of tryptophan but 31 g (0.21 mol) of methionine. According to this study, the body of an average young man requires about seven times as many moles of methionine as it does of tryptophan to carry out the processes involving amino acids.

Proteins in foods are classified as **complete proteins** if they contain all the essential amino acids in the proper proportions needed by the body. Protein foods that do not meet this requirement are classified as incomplete. Several protein-containing foods are shown in **Figure 22.7**.

complete protein Protein in food that contains all essential amino acids in the proportions needed by the body.

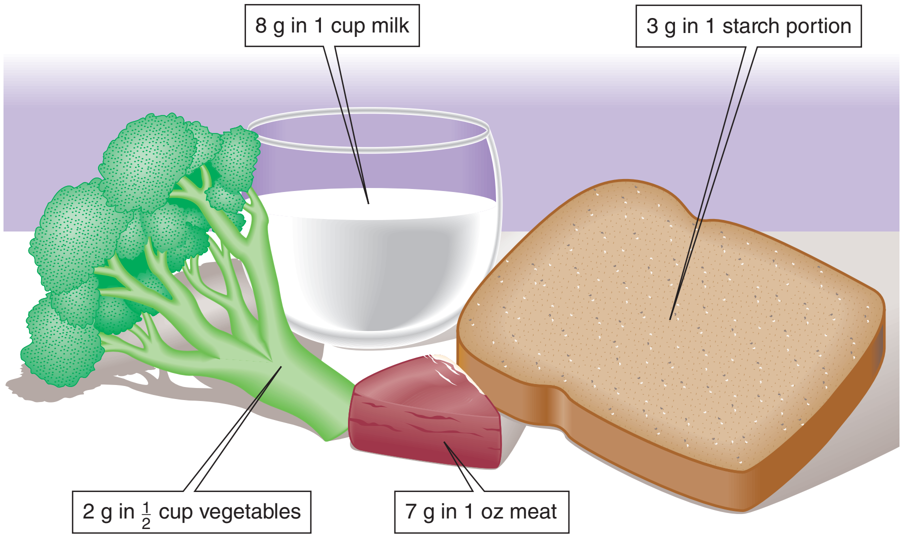


FIGURE 22.7 The protein content of several foods.

TABLE 22.2 The Essential Amino Acids

- Histidine
- Isoleucine
- Leucine
- Lysine
- Methionine
- Phenylalanine
- Threonine
- Tryptophan
- Valine

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 22.1 Describing Functions of Macronutrients

List a primary function for each of the macronutrients:

a. Carbohydrates
b. Lipids
c. Proteins

Solution

a. Energy source for body functions
b. Concentrated energy source for body functions
c. Production of new tissue

✔ **LEARNING CHECK 22.1** List another primary function for each macronutrient:

a. Carbohydrates
b. Lipids
c. Proteins

Keystone Pictures USA/Keystone Press/Alamy Stock Photo

FIGURE 22.8 Dorothy Crowfoot Hodgkin was awarded the Nobel Prize for Chemistry in 1964 for determining the complicated structure of vitamin B_{12}.

Swetlana Wall/Shutterstock.com

FIGURE 22.9 Although oranges are recognized as a good source of vitamin C (50 mg per 100 g), strawberries (60 mg per 100 g) and cauliflower (70 mg per 100 g) are even better.

22.3 Micronutrients I: Vitamins

Learning Objective 3 Distinguish between and classify vitamins as water-soluble or fat-soluble on the basis of name and behavior in the body.

Vitamins are organic micronutrients that the body cannot produce in amounts needed for good health. The highly polar nature of some vitamins renders them water-soluble. Nine water-soluble vitamins have been identified. Some are designated by names, some by letters, and some by letters and numbers, such as vitamin B_{12} (see **Figure 22.8**). **Table 22.3** presents the names nutritionists use (the "correct" names), along with other common names you will likely encounter in books and on product labels. With the exception of vitamin C (see **Figure 22.9**), all water-soluble vitamins have been shown to function as coenzymes.

Some vitamins (A, D, E, and K) have very nonpolar molecular structures and therefore dissolve only in nonpolar solvents. In the body, the nonpolar solvents are the lipids we have classified as fats, so these vitamins are called fat-soluble. The fat-soluble vitamins have diverse functions in the body, and they act somewhat like hormones (**Table 22.3**). Care must be taken to avoid overdoses of the fat-soluble vitamins. Toxic effects are known to occur, especially with vitamin A, when excess amounts of these vitamins accumulate in body tissue. Excesses of water-soluble vitamins are excreted readily through the kidneys and are not normally a problem.

Example 22.2 Classifying Vitamins

Identify each of the following vitamins as water-soluble or fat-soluble:

a. Folic acid
b. A
c. D

Solution

a. Water-soluble
b. Fat-soluble
c. Fat-soluble

✔ **LEARNING CHECK 22.2** Identify the four fat-soluble vitamins.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

TABLE 22.3 Vitamin Sources, Functions, and Deficiency Conditions

Vitamin	Dietary Sources	Functions	Deficiency Conditions
Water-soluble			
B_1 (thiamin)	Bread, beans, nuts, milk, peas, pork, rice bran	Coenzyme in decarboxylation reactions	Beriberi: nausea, severe exhaustion, paralysis
B_2 (riboflavin)	Milk, meat, eggs, dark green vegetables, bread, beans, peas	Forms the coenzymes FMN and FAD, which are hydrogen transporters	Dermatitis (skin problems)
Niacin	Meat, whole grains, poultry, fish	Forms the coenzyme NAD^+, which is a hydride transporter	Pellagra: weak muscles, no appetite, diarrhea, dermatitis
B_6 (pyridoxine)	Meat, whole grains, poultry, fish	Coenzyme form carries amino and carboxyl groups	Dermatitis, nervous disorders
B_{12} (cobalamin)	Meat, fish, eggs, milk	Coenzyme in amino acid metabolism	Rare except in vegetarians; pernicious anemia
Folic acid	Leafy green vegetables, peas, beans	Coenzyme in methyl group transfers	Anemia
Pantothenic acid	All plants and animals, nuts; whole-grain cereals	Part of coenzyme A, acyl group carrier	Anemia
Biotin	Found widely; egg yolk, liver, yeast, nuts	Coenzyme form used in fatty acid synthesis	Dermatitis, muscle weakness
C (ascorbic acid)	Citrus fruits, tomatoes, green pepper, strawberries, leafy green vegetables	Synthesis of collagen for connective tissue	Scurvy: tender tissues; weak, bleeding gums; swollen joints
Fat-soluble			
A (retinol)	Eggs, butter, cheese, dark green and deep orange vegetables	Synthesis of visual pigments	Inflamed eye membranes, night blindness, scaliness of skin
D (calciferol)	Fish-liver oils, fortified milk	Regulation of calcium and phosphorus metabolism	Rickets (malformation of the bones)
E (tocopherol)	Whole-grain cereals, margarine, vegetable oil	Prevention of oxidation of vitamin A and fatty acids	Breakage of red blood cells
K	Cabbage, potatoes, peas, leafy green vegetables	Synthesis of blood-clotting substances	Blood-clotting disorders

HEALTH CONNECTIONS **22.1**

Select a Heart-Healthful Diet

People make food choices in the context of cultural norms and lifelong habits. Regional foods and family practices become part of our lives from birth. Families pass down food traditions to each generation. These food choices become deeply ingrained habits. If your food-choice inheritance is not healthful, it can be difficult to change your dietary habits.

Making changes requires education. Knowing what foods to choose, and why, allows you to make healthful choices. Since heart health is the cornerstone of longevity, shaping your diet to meet heart-health goals is a good place to start. Here are some guidelines for fostering a healthy heart:

1. Be aware of portion size.

Portion size is a fundamental part of a healthful diet. In America, portion size has increased over time to unhealthful proportions. Most restaurant portions are made too large in an attempt to convince customers that they are getting "more for their money." However, eating all that food ensures that it is going to "waist."

2. Eat a plant-based diet.

Research shows that diets low in calories, low in fats, high in fiber, and high in phytochemicals, such as lycopene, promote heart health. Dieticians recommend building your meals around fruits and vegetables, including whole grains.

3. Choose healthful proteins.

Muscle meats—such as pork, beef, lamb, and veal, as well as processed meats—are not healthful additions to a heart healthful diet. Choose lean meats such as fish and skinless chicken or turkey.

4. Limit unhealthful fats.

Saturated and trans fats are known to contribute to coronary artery disease; therefore limiting these unhealthful fats is an important part of a heart-healthful diet.

5. Reduce sodium intake.

High sodium intake contributes to high blood pressure, which is an important risk factor in heart disease. Healthy adults should not exceed an intake of 2300 mg of sodium per day. This is the amount of sodium in about a half teaspoon of table salt.

6. Allow an occasional treat.

Since dietary habits are significant parts of our behavior, changing too much too soon can undermine your success. This will help you stay on track by avoiding an all-or-nothing mentality.

Strive to eat heart-healthful foods every day, so you can reap the benefits of a long and healthy life.

Ksenia Perminova/Shutterstock.com

Allow yourself an occasional treat.

22.4 Micronutrients II: Minerals

Learning Objective 4 List a primary function in the body for each major mineral.

mineral A metal or nonmetal used in the body in the form of ions or compounds.

The word **mineral** is generally used to describe inorganic substances, often as if they were in the elemental form. Thus, we might hear that a food is a good source of phosphorus, when in fact the food does not contain elemental phosphorus, a caustic nonmetal, but probably contains phosphate ions such as HPO_4^{2-} and $H_2PO_4^{-}$ or, more likely, organic substances that contain phosphorus, such as nucleic acids and phospholipids.

major mineral A mineral found in the body in quantities greater than 5 g.

trace mineral A mineral found in the body in quantities smaller than 5 g.

In the body, the elements classified as minerals are never used in elemental form, but rather in the form of ions or compounds. They are classified as **major minerals** and **trace minerals** on the basis of the amount present in the body, as shown in **Figure 22.10**. In general, the major minerals are required in larger daily amounts than are the trace minerals. For example, the RDIs for calcium and phosphorus, the major minerals found in the body in largest amounts, are 800 mg. The RDIs for iron and iodine, two of the trace minerals, are 10–18 mg and 0.12 mg, respectively. By way of comparison, the RDIs for vitamin C and niacin are 55–60 mg and 18 mg, respectively.

As shown in **Table 22.4**, the functions of minerals are consistent with their classification as major or trace and with the amount required daily in the diet. For example, compounds

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

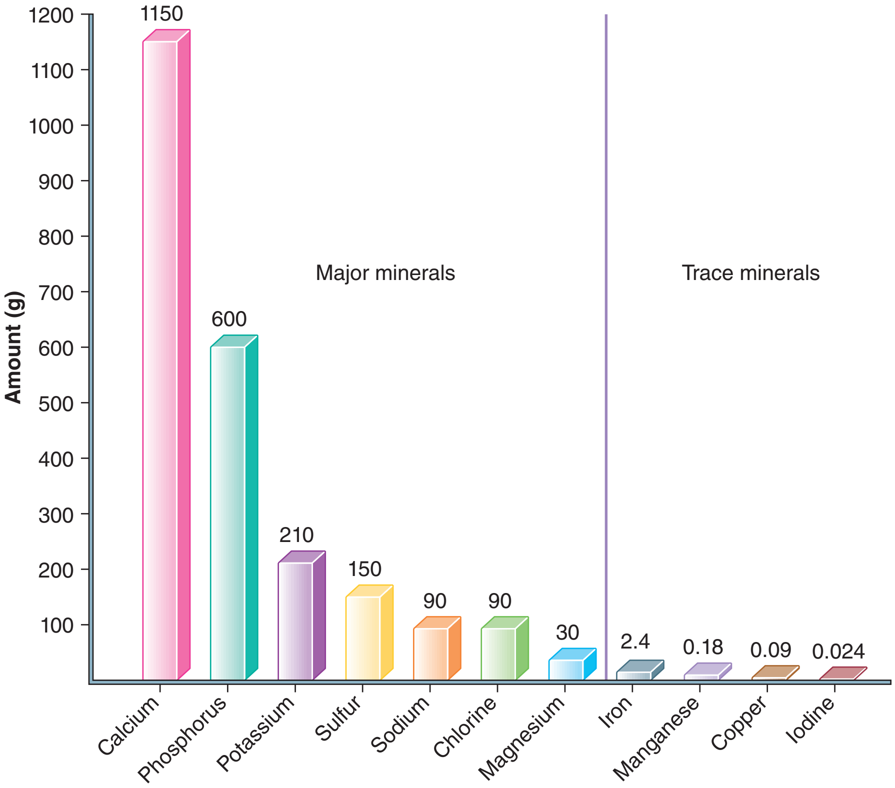
TABLE 22.4 Major and Trace Mineral Sources, Functions, and Deficiency Conditions

Mineral	Dietary Sources	Functions	Deficiency Conditions
Major minerals			
Calcium	Dairy foods, dark green vegetables	Bone and teeth formation, blood clotting, nerve impulse transmission	Stunted growth, rickets, weak and brittle bones
Chlorine	Table salt, seafood, meat	HCl in gastric juice, acid–base balance	Muscle cramps, apathy, excessive bleeding, reduced appetite
Magnesium	Whole-grain cereals, meat, nuts, milk, legumes	Activation of enzymes, protein synthesis	Inhibited growth, weakness, spasms
Phosphorus	Milk, cheese, meat, fish, grains, legumes, nuts	Enzyme component, acid–base balance, bone and tooth formation	Weakness, calcium loss, weak bones
Potassium	Meat, milk, many fruits, cereals, legumes	Acid–base and water balance, nerve function	Muscle weakness, paralysis
Sodium	Most foods except fruit	Acid–base and water balance, nerve function	Muscle cramps, apathy, reduced appetite
Sulfur	Protein foods	Component of proteins	Deficiencies are very rare
Trace minerals			
Arsenic[a]	Many foods	Growth and reproduction	Poor growth and reproduction
Cobalt	Meat, liver, dairy foods	Component of vitamin B_{12}	Pernicious anemia (vitamin-deficiency symptom)
Copper	Drinking water, liver, grains, legumes, nuts	Component of numerous enzymes, hemoglobin formation	Anemia, fragility of arteries, low appetite, and inhibited growth
Chromium	Fats, vegetable oils, grains, meat	Enhances insulin action	Reduced ability to metabolize glucose
Fluorine	Drinking water, seafood, onions, spinach	Maintenance of bones and teeth	Higher frequency of tooth decay
Iodine	Iodized salt, fish, dairy products	Component of thyroid hormones	Hypothyroidism, goiter
Iron	Liver, lean meat, whole grains, dark green vegetables	Component of enzymes and hemoglobin	Anemia
Manganese	Grains, beet greens, legumes, fruit	Component of enzymes	Deficiencies are rare
Molybdenum	Legumes, cereals, organ meats, dark green vegetables	Component of enzymes	Deficiencies are rare
Nickel	Many foods	Needed for health of numerous tissues	Organ damage, deficiencies are rare
Selenium	Grains, meat, poultry, milk	Component of enzymes	Deficiencies are rare
Silicon[a]	Many foods	Bone calcification	Poor bone development, deficiencies are rare
Tin[a]	Many foods	Needed for growth	Poor growth
Vanadium[a]	Many foods	Growth, bone development, reproduction	Poor growth, bone development, and reproduction
Zinc	Milk, liver, shellfish, wheat bran	Component of numerous enzymes	Poor growth, lack of sexual maturation, loss of appetite, abnormal glucose tolerance

[a] Need and deficiency symptoms determined for animals, probable in humans, but not yet recognized.

of some major minerals (Ca and P) are the primary inorganic structural components of bones and teeth. Other major minerals (Na, K, Cl, and Mg) form principal ions that are distributed throughout the body's various fluids. Some trace minerals are components of vitamins (Co), enzymes (Zn and Se), hormones (I), or specialized proteins (Fe and Cu). Thus, we see that even though trace minerals are required in small quantities, their involvement in critical enzymes, hormones, and the like makes them equally as important for good health as the major minerals.

FIGURE 22.10 Minerals in a 60-kg person. The major minerals are those present in amounts larger than 5 g (a teaspoon); only four of the numerous trace minerals are shown. Only calcium and phosphorus appear in amounts larger than a pound (454 g).



Example 22.3 Identifying Mineral Functions

Identify a mineral that fits each of the following descriptions:

a. A component of thyroid hormones
b. A component of vitamin B_{12}
c. Present in gastric juice

Solution

a. Iodine
b. Cobalt
c. Chlorine

✔ **LEARNING CHECK 22.3** Identify a mineral associated with each of the following deficiency conditions:

a. Pernicious anemia
b. Higher frequency of tooth decay
c. Goiter

22.5 The Flow of Energy in the Biosphere

Learning Objective 5 Describe the major steps in the flow of energy in the biosphere.

The sun is the ultimate source of energy used in all biological processes. The sun's enormous energy output is the result of the fusion of hydrogen atoms into helium atoms. The net reaction for this process is:

$$4\text{H} \xrightarrow{\text{nuclear fusion}} \text{He} + \text{energy} \qquad (22.1)$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

A portion of the liberated energy reaches Earth as sunlight and is absorbed by chlorophyll pigments in plants. In the plants, the energy drives the reactions of photosynthesis that convert carbon dioxide and water first into glucose, and then into starch, triglycerides, and other storage forms of energy. The net reaction for glucose production is:

$$6CO_2 + 6H_2O + \text{energy} \xrightarrow{\text{photosynthesis}} \underset{\text{glucose}}{C_6H_{12}O_6} + 6O_2 \qquad (22.2)$$

All animals obtain energy either directly or indirectly from these energy stores in plants.

During **cellular respiration**, both plants and animals combine these energy-rich compounds with oxygen from the air, producing carbon dioxide and water, and releasing energy. Cellular respiration, which should not be confused with pulmonary respiration (breathing), is represented as:

cellular respiration The entire process involved in the use of oxygen by cells.

$$\text{glucose and other storage forms of energy} + O_2 \xrightarrow{\text{respiration}} CO_2 + H_2O + \text{energy released} \qquad (22.3)$$

A portion of the energy released during respiration is captured within the cells in the form of adenosine triphosphate (ATP), a chemical carrier of energy, from which energy can be obtained and used directly for the performance of biological work. The remainder of the energy from respiration is liberated as heat. Steps in the flow of energy in the biosphere are summarized in **Figure 22.11**.

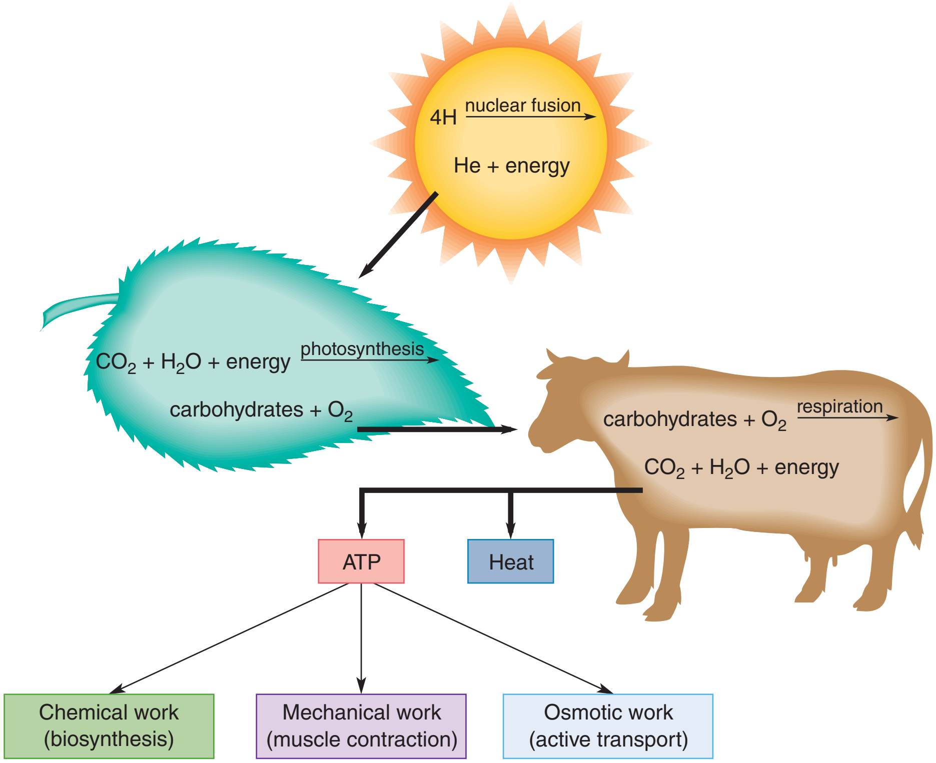
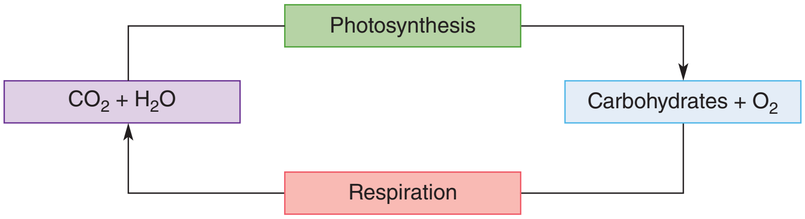

4H
nuclear fusion
He + energy
CO₂ + H₂O + energy
photosynthesis
carbohydrates + O₂
carbohydrates + O₂
respiration
CO₂ + H₂O + energy
ATP
Heat
Chemical work
(biosynthesis)
Mechanical work
(muscle contraction)
Osmotic work
(active transport)

FIGURE 22.11 Energy flow in the biosphere.

Notice in **Figure 22.11** that atmospheric carbon dioxide is the initial source of carbon for carbohydrates. Another important feature of **Figure 22.11** is that overall, the respiration process is the reverse of the photosynthetic process. Thus, some of Earth's carbon compounds are repeatedly recycled by living organisms (see **Figure 22.12**).

FIGURE 22.12 A simplified carbon cycle.



22.6 Metabolism and an Overview of Energy Production

Learning Objectives 6 Differentiate among metabolism, anabolism, and catabolism.

Learning Objectives 7 Outline the three stages in the extraction of energy from food.

22.6A Metabolism

Living cells are very active chemically, with thousands of different reactions occurring at the same time. The sum total of all the chemical reactions involved in maintaining a living cell is called **metabolism**. The reactions of metabolism are divided into two categories, catabolism and anabolism. **Catabolism** consists of all reactions that lead to the breakdown of biomolecules. **Anabolism** includes all reactions that lead to the synthesis of biomolecules. In general, energy is released during catabolism and required during anabolism.

metabolism The sum of all reactions occurring in an organism.

catabolism All reactions involved in the breakdown of biomolecules.

anabolism All reactions involved in the synthesis of biomolecules.

metabolic pathway A sequence of reactions used to produce one product or accomplish one process.

A characteristic of all living organisms is a high degree of order in their structures and chemical processes. Even the simplest organisms exhibit an enormous array of chemical reactions that are organized into orderly, well-regulated sequences known as **metabolic pathways**. Each metabolic pathway consists of a series of consecutive chemical reactions or steps that convert a starting material into an end product. For example, two pathways that will be covered in **Chapter 23** are the citric acid cycle and the electron transport chain.

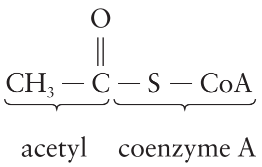
Fortunately for those who study the biochemistry of living systems, a great many similarities exist among the major metabolic pathways found in all life forms. These similarities enable scientists to study the metabolism of simple organisms and use the results to help explain the corresponding metabolic pathways in more complex organisms, including humans. This text concentrates on human biochemistry, but you should realize that much of what is said about human metabolism can be applied equally well to the metabolism of most other organisms.

22.6B The Catabolism of Food

The three stages involved in the catabolic extraction of energy from food are illustrated in **Figure 22.13**.

Stage I is digestion, in which large, complex molecules are chemically broken into relatively small, simple ones (see **Figure 22.14**). The most common reaction in digestion is hydrolysis, in which proteins are converted to amino acids, carbohydrates are converted to monosaccharides (primarily glucose, galactose, and fructose), and fats are converted to fatty acids and glycerol. The smaller molecules are then absorbed into the body through the lining of the small intestine.

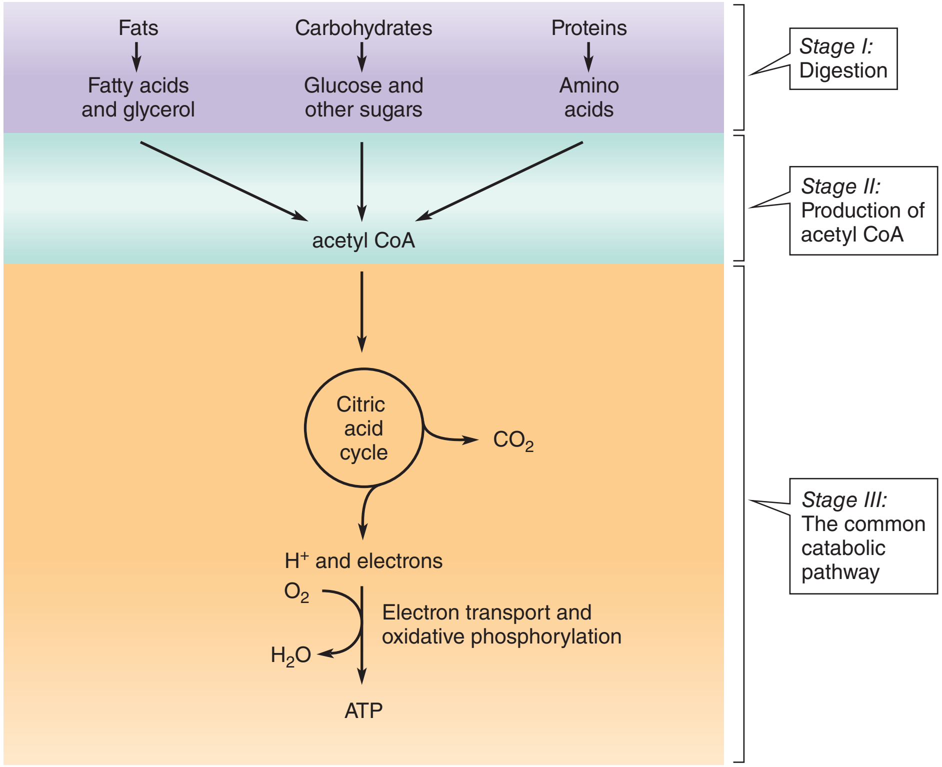
In Stage II, the small molecules from digestion are degraded to even simpler units, primarily the two-carbon acetyl portion of acetyl coenzyme A (acetyl CoA):



$$\underbrace{\mathrm{CH_3}-\overset{\displaystyle \mathrm{O}}{\overset{\|}{\mathrm{C}}}}_{\text{acetyl}}-\underbrace{\mathrm{S}-\mathrm{CoA}}_{\text{coenzyme A}}$$

Some energy is released in the second stage, but much more is produced during the oxidation of the acetyl units of acetyl CoA in the third stage. Stage III consists of the citric acid

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.



Fats
Carbohydrates
Proteins
Fatty acids and glycerol
Glucose and other sugars
Amino acids
acetyl CoA
Citric acid cycle
CO_2
H^+ and electrons
O_2
H_2O
Electron transport and oxidative phosphorylation
ATP
Stage I: Digestion
Stage II: Production of acetyl CoA
Stage III: The common catabolic pathway

FIGURE 22.13 The three stages in the extraction of energy from food.

$$\text{proteins} \xrightarrow{\text{hydrolysis}} \text{amino acids}$$

$$\text{disaccharides and polysaccharides} \xrightarrow{\text{hydrolysis}} \text{monosaccharides}$$

$$\text{fats and oils} \xrightarrow{\text{hydrolysis}} \text{fatty acids} + \text{glycerol}$$

FIGURE 22.14 The digestion of food involves enzyme-catalyzed hydrolysis reactions.

cycle followed by electron transport chain and oxidative phosphorylation. Because the reactions of Stage III are the same regardless of the type of food being degraded, Stage III is sometimes referred to as the **common catabolic pathway**. Energy released during Stage III appears in the form of energy-rich molecules of ATP. The whole purpose of the catabolic pathway is to convert the chemical energy in foods to molecules of ATP. The common catabolic pathway will be covered in Chapter 23. **Chapters 23** to **25** discuss the ways in which carbohydrates, lipids, and proteins provide molecules that are degraded by reactions of the common catabolic pathway (see **Figure 22.15**).

common catabolic pathway The reactions of the citric acid cycle plus those of the electron transport chain and oxidative phosphorylation.

Example 22.4 Identify Stages of Energy Extraction

Identify the stage of energy extraction associated with each of the following:

a. Oxidative phosphorylation
b. Digestion
c. Citric acid cycle

Solution

a. Stage III
b. Stage I
c. Stage III

Christopher Meder/Shutterstock.com

FIGURE 22.15 All organisms use metabolic pathways to obtain the energy needed for life.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

✔ **LEARNING CHECK 22.4** Identify the stage of energy extraction associated with each of the following:

a. Electron transport
b. Conversion of fats to fatty acids and glycerol
c. Production of acetyl CoA

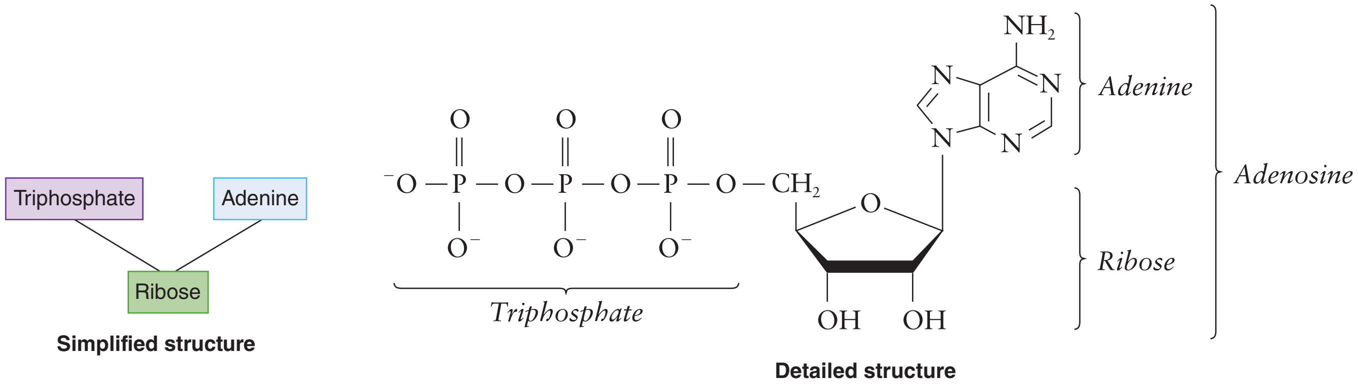
22.7 ATP: The Primary Energy Carrier

Learning Objective 8 Explain how ATP plays a central role in the production and use of cellular energy.

Certain bonds in ATP store the energy released during the oxidation of carbohydrates, lipids, and proteins. ATP molecules act as energy carriers and deliver the energy to the parts of the cell where energy is needed to power muscle contraction, biosynthesis, and other cellular work.

22.7A The Structure and Hydrolysis of ATP

The structure of the ATP molecule is relatively simple (see **Figure 22.16**). It consists of a heterocyclic base, adenine, bonded to the sugar ribose. Taken together, this portion of the molecule is called adenosine. The triphosphate portion is bonded to the ribose to give adenosine triphosphate, or ATP. At the cell pH of 7.4, all the protons of the triphosphate group are ionized, giving the ATP molecule a charge of −4. In the cell, ATP is complexed with Mg^{2+} in a 1:1 ratio. Thus, the 1:1 complex exhibits a net charge of −2. Two other triphosphates—GTP, containing the base guanine, and UTP, containing the base uracil—are important in carbohydrate metabolism (see **Chapter 23**).

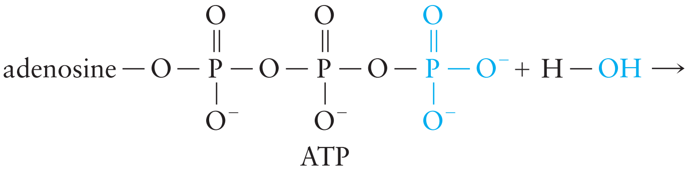


Simplified structure

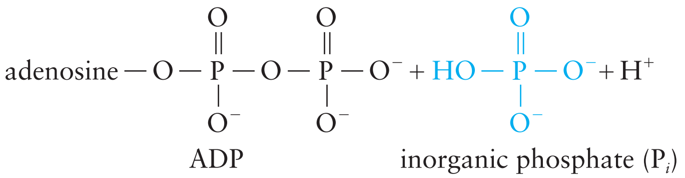
Detailed structure

FIGURE 22.16 The structure of ATP.

The triphosphate end of ATP is the part of the molecule that is important in the transfer of biochemical energy. The key reaction in this energy delivery system is the transfer of a phosphoryl group, $—PO_3^{2-}$, from ATP to another molecule. For example, during the hydrolysis of ATP in water, a phosphoryl group is transferred from ATP to water. The products of this hydrolysis are adenosine diphosphate (ADP) and a phosphate ion, often referred to as an inorganic phosphate, P_i, or simply as *phosphate*.



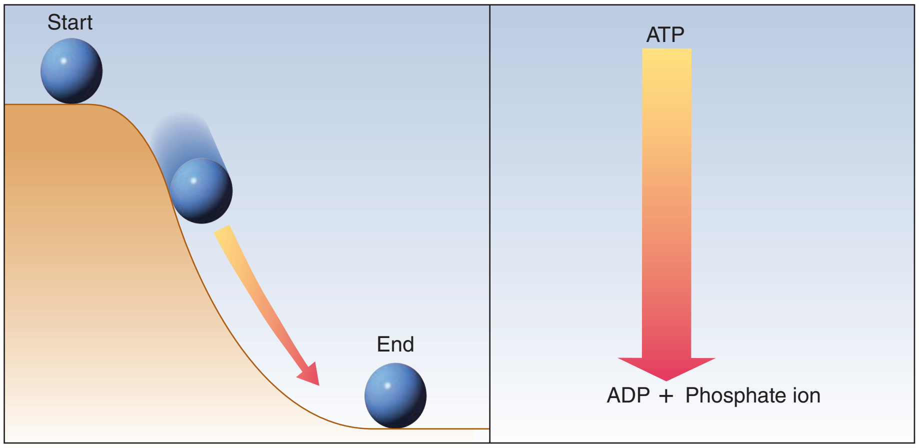
$$\underbrace{\text{adenosine}-O-\overset{\overset{\displaystyle O}{\|}}{\underset{\underset{\displaystyle O^-}{|}}{P}}-O-\overset{\overset{\displaystyle O}{\|}}{\underset{\underset{\displaystyle O^-}{|}}{P}}-O-\overset{\overset{\displaystyle O}{\|}}{\underset{\underset{\displaystyle O^-}{|}}{P}}-O^-}_{\text{ATP}} + H-OH \longrightarrow$$



$$\text{adenosine}-O-\overset{\overset{\large O}{\|}}{\underset{\underset{\large O^-}{|}}{P}}-O-\overset{\overset{\large O}{\|}}{\underset{\underset{\large O^-}{|}}{P}}-O^- + HO-\overset{\overset{\large O}{\|}}{\underset{\underset{\large O^-}{|}}{P}}-O^- + H^+ \qquad (22.4)$$

The transfer of a phosphoryl group from ATP to water is accompanied by a release of energy. This energy is called free energy and is represented by the symbol ΔG. When energy is released by a reaction or process, ΔG will have a negative value. When energy is absorbed, ΔG will have a positive value. When ΔG is measured under standard conditions (temperature, concentration, etc.), it is represented by ΔG°, and a superscript prime ($\Delta G^{\circ\prime}$) is added if ΔG° is measured at body conditions. The liberated free energy is available for use by the cell to carry out processes requiring an input of energy. This energy-releasing hydrolysis reaction (see **Figure 22.17**) is represented by the following equation:

$$ATP + H_2O \rightarrow ADP + P_i + H^+ \quad \Delta G^{\circ\prime} = -7.3 \text{ kcal/mol} \qquad (22.5)$$



a A ball rolls down a hill, releasing potential energy.

b ATP is hydrolyzed to produce ADP and phosphate ion, releasing energy. The release of energy when a ball rolls down a hill is analogous to the release of energy in a chemical reaction.

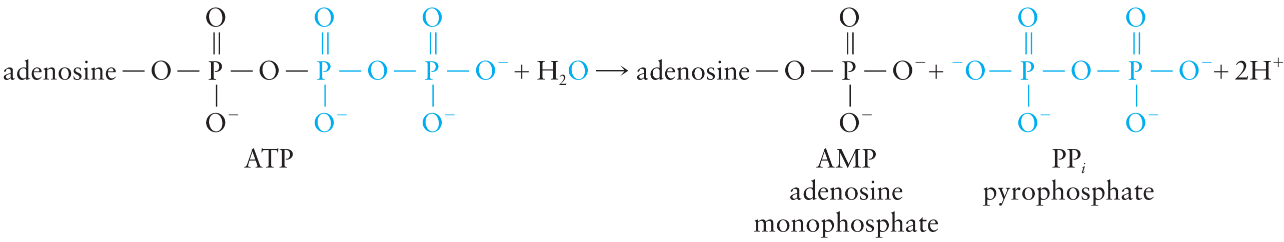
FIGURE 22.17 Schematic representation of the lowering of energy. From Campbell, *Biochemistry*, 9E. © 2018 Cengage Learning.

Many other phosphate-containing compounds found in biological systems also liberate energy on hydrolysis. Several are listed in **Table 22.5**, along with values for their free standard energy of hydrolysis.

Compounds that liberate a great amount of free energy on hydrolysis are called **high-energy compounds**. Remember, a negative sign for $\Delta G^{\circ\prime}$ means the energy is liberated when the reaction takes place. Thus, ATP ($\Delta G^{\circ\prime} = -7.3$ kcal/mol) is considered a high-energy compound, but not the only one found in cells, as you can see from **Table 22.5**.

high-energy compound A substance that on hydrolysis liberates a great amount of free energy.

The hydrolysis of ATP to ADP is the principal energy-releasing reaction for ATP. However, some other hydrolysis reactions also play important roles in energy transfer. An example is the hydrolysis of ATP to adenosine monophosphate (AMP) and pyrophosphate (PP_i):



$$\text{adenosine}-O-\overset{\overset{\large O}{\|}}{\underset{\underset{\large O^-}{|}}{P}}-O-\overset{\overset{\large O}{\|}}{\underset{\underset{\large O^-}{|}}{P}}-O-\overset{\overset{\large O}{\|}}{\underset{\underset{\large O^-}{|}}{P}}-O^- + H_2O \longrightarrow \text{adenosine}-O-\overset{\overset{\large O}{\|}}{\underset{\underset{\large O^-}{|}}{P}}-O^- + {}^-O-\overset{\overset{\large O}{\|}}{\underset{\underset{\large O^-}{|}}{P}}-O-\overset{\overset{\large O}{\|}}{\underset{\underset{\large O^-}{|}}{P}}-O^- + 2H^+ \qquad (22.6)$$

STUDY TOOLS 22.1

Bioprocesses

The last four chapters of the text complete our study of the molecular basis of life. This chapter and the next three build on your knowledge of the biomolecules (carbohydrates, lipids, proteins, and nucleic acids) and examine the processes that support living organisms. Your attention should now be directed toward gaining an understanding of these processes, where they occur in the cell, their purpose, and, in some cases, key summary reactions. A number of detailed pathways such as glycolysis, the fatty acid spiral, and the urea cycle will be presented. Don't let the numerous reactions in these pathways intimidate you. Although each reaction could be looked at individually, we have tried to help you focus your attention by emphasizing the overall importance of each pathway by identifying its purpose, cellular location, starting material, products, energy requirements, and regulation.

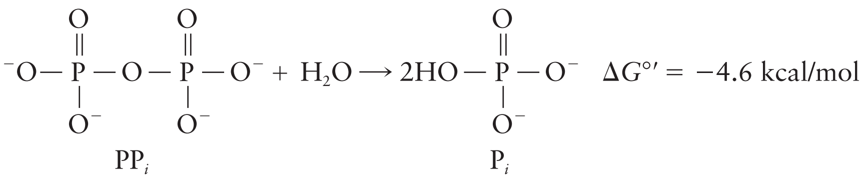
TABLE 22.5 Free Energy Changes for the Hydrolysis of Some Phosphate Compounds

Reaction			$\Delta G°'$ (kcal/mol)
Phosphoenolpyruvate + H_2O	→	pyruvate + phosphate	−14.8
Carbamoyl phosphate + H_2O	→	ammonia + CO_2 + phosphate	−12.3
1,3-bisphosphoglycerate + H_2O	→	3-phosphoglycerate + phosphate	−11.8
Phosphocreatine + H_2O	→	creatine + phosphate	−10.3
ATP + H_2O	→	ADP + phosphate	−7.3
ADP + H_2O	→	AMP + phosphate	−7.3
Glucose-1-phosphate + H_2O	→	glucose + phosphate	−5.0
AMP + H_2O	→	adenosine + phosphate	−3.4
Glucose-6-phosphate + H_2O	→	glucose + phosphate	−3.3
Glycerol-3-phosphate + H_2O	→	glycerol + phosphate	−2.2

The reaction may also be written as:

$$\text{ATP} + H_2O \rightarrow \text{AMP} + \text{PP}_i + 2H^+ \qquad \Delta G°' = -10.9 \text{ kcal/mol} \qquad (22.7)$$

When the hydrolysis of ATP to AMP occurs during metabolism, it is usually followed by the immediate hydrolysis of the pyrophosphate, which releases even more free energy:



$$^{-}O-\underset{\underset{O^-}{|}}{\overset{\overset{O}{\|}}{P}}-O-\underset{\underset{O^-}{|}}{\overset{\overset{O}{\|}}{P}}-O^- + H_2O \longrightarrow 2HO-\underset{\underset{O^-}{|}}{\overset{\overset{O}{\|}}{P}}-O^- \qquad \Delta G°' = -4.6 \text{ kcal/mol} \qquad (22.8)$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The hydrolyses of ATP and related compounds are summarized in **Table 22.6**.

TABLE 22.6 Hydrolyses of Some ATP-Related Compounds

Reaction			$\Delta G°'$ (kcal/mol)
ATP + H_2O	→	ADP + P_i + H^+	−7.3
ATP + H_2O	→	AMP + PP_i + $2H^+$	−10.9
PP_i + H_2O	→	$2P_i$	−4.6
ADP + H_2O	→	AMP + P_i + H^+	−7.3

22.7B The ATP–ADP Cycle

In biological systems, ATP functions as an immediate donor of free energy rather than as a storage form of free energy. In a typical cell, an ATP molecule is hydrolyzed within one minute following its formation. Thus, the turnover rate of ATP is very high. For example, a resting human body hydrolyzes ATP at the rate of about 40 kg every 24 hours. During strenuous exertion, this rate of ATP utilization may be as high as 0.5 kg per minute. Motion, biosynthesis, and other forms of cellular work can occur only if ATP is continuously regenerated from ADP. **Figure 22.18** depicts the central role served by the ATP–ADP cycle in linking energy production with energy utilization.

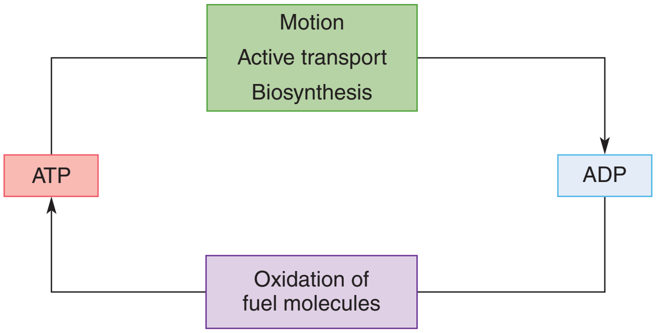


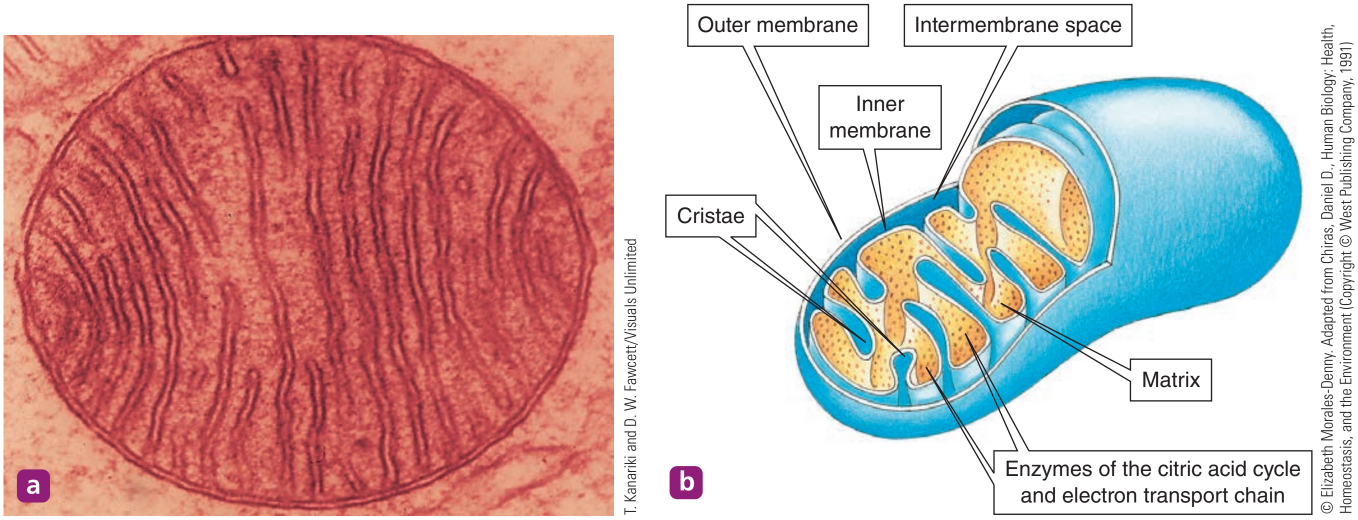
FIGURE 22.18 The ATP–ADP cycle. ATP, which supplies the energy for cellular work, is continuously regenerated from ADP during the oxidation of fuel molecules.

22.7C Mitochondria

Enzymes that catalyze the formation of ATP, as well as the other processes in the common catabolic pathway, are all located within the cell in organelles called **mitochondria** (see **Figure 22.19**). Mitochondria are often called cellular "power stations" because they are the sites for most ATP synthesis in the cells.

mitochondrion A cellular organelle in which reactions of the common catabolic pathway occur.

A mitochondrion contains both inner and outer membranes. As a result of extensive folding, the inner membrane has a surface area that is many times that of the outer membrane. The folds of the inner membrane are called *cristae*, and the gel-filled space that surrounds them is called the *matrix*. The enzymes for ATP synthesis (electron transport and oxidative phosphorylation) are located on the matrix side of the cristae. The enzymes for the citric acid cycle are found within the matrix, attached or near to the surface of the inner membrane. Thus, all the enzymes involved in the common catabolic pathway are in close proximity.



T. Kanariki and D. W. Fawcett/Visuals Unlimited

© Elizabeth Morales-Denny. Adapted from Chiras, Daniel D., Human Biology: Health, Homeostasis, and the Environment (Copyright © West Publishing Company, 1991)

FIGURE 22.19 The mitochondrion: (**a**) a photomicrograph; (**b**) a schematic drawing, cut away to reveal the internal organization.

22.8 Important Coenzymes in the Common Catabolic Pathway

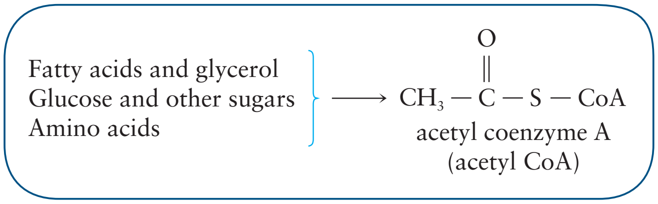
Learning Objective 9 Explain the role of coenzymes in the common catabolic pathway.

As discussed in **Section 20.3**, coenzymes often participate in enzyme-catalyzed reactions by acting as shuttle systems in the transfer of chemical groups from one compound to another. For example, a coenzyme may accept hydrogen from one compound and later donate hydrogen to another compound. We also pointed out that many important coenzymes are formed from vitamins. The three substances discussed in this section exhibit both of these coenzyme characteristics.

22.8A Coenzyme A

Coenzyme A is a central compound in metabolism. It is a part of acetyl coenzyme A (acetyl CoA), the substance formed from all foods as they pass through Stage II of catabolism (see **Figure 22.20**).

FIGURE 22.20 Stage II of the oxidation of foods. Acetyl CoA is formed as the pathways of catabolism converge.



$$\left.\begin{array}{l}\text{Fatty acids and glycerol}\\ \text{Glucose and other sugars}\\ \text{Amino acids}\end{array}\right\} \longrightarrow \mathrm{CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-S-CoA}$$

acetyl coenzyme A
(acetyl CoA)

Coenzyme A is derived from the B vitamin pantothenic acid (B_5) (see **Figure 22.21**). It also contains two other components, a phosphate derivative of ADP and b-mercaptoethylamine. A key feature in the structure of coenzyme A is the presence of the sulfhydryl group (—SH), which is the reactive portion of the molecule. For this reason, coenzyme A is often abbreviated as CoA—SH.

The letter *A* is included in the coenzyme name to signify its participation in the transfer of acetyl groups. It is now known that coenzyme A transfers acyl groups in general rather than just the acetyl group. This is demonstrated in fatty acid oxidations (see **Section 24.4**), fatty acid synthesis (see **Section 24.7**), and other biological

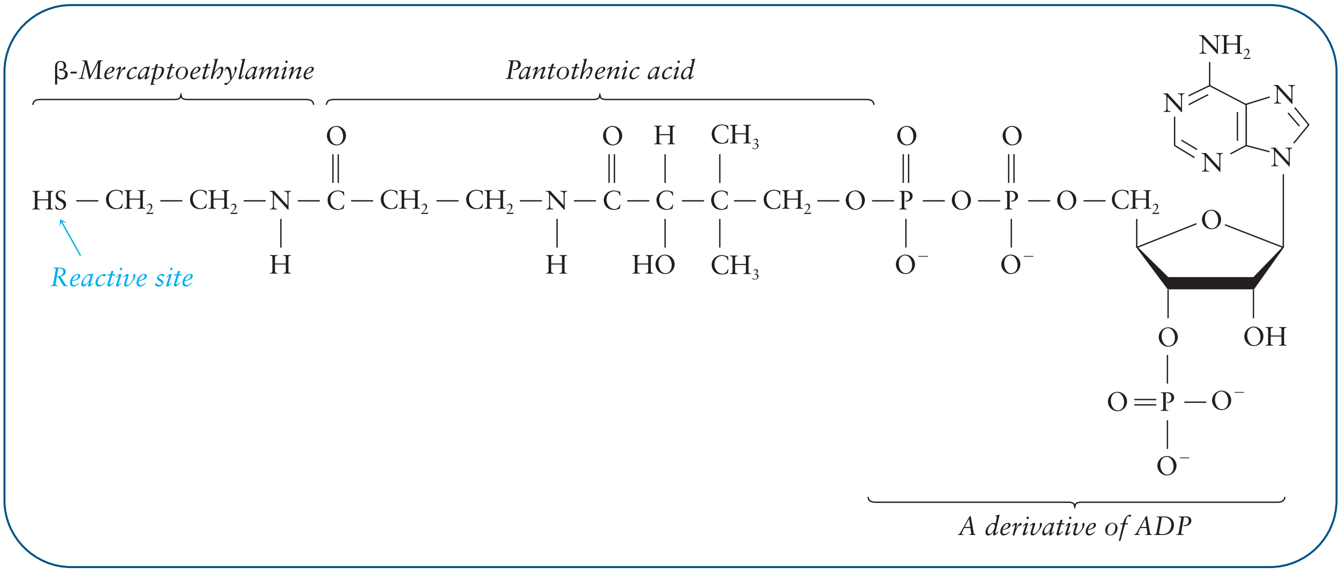
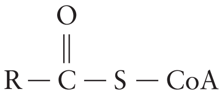


FIGURE 22.21 The structure of coenzyme A. The sulfhydryl group (—SH) is the reactive site.

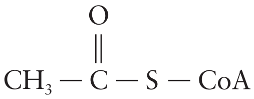
reactions. Acyl groups are linked to coenzyme A through the sulfur atom in a **thioester bond**.

thioester bond The carbon–sulfur bond of the $-\overset{\overset{\Large O}{\|}}{C}-S-$ functional group.



$$R-\overset{\overset{O}{\|}}{C}-S-CoA$$

acyl CoA



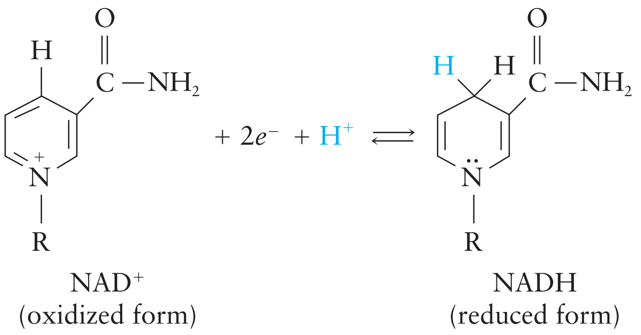
$$CH_3-\overset{\overset{O}{\|}}{C}-S-CoA$$

acetyl CoA

22.8B The Coenzymes NAD$^+$ and FAD

The majority of energy for ATP synthesis is released when the oxygen we breathe is reduced. During that process, oxygen accepts electrons and hydrogen ions, and water is produced. The electrons come from the oxidation of fuel molecules, such as glucose, but the electrons are not transferred directly to the oxygen from the fuel molecules or their breakdown products. Instead, these substrates first transfer the electrons to special coenzyme carriers. The reduced forms of these coenzymes then transfer the electrons to oxygen through the reactions of the electron transport chain. ATP is formed from ADP and P_i as a result of this flow of electrons.

The first of these coenzymes, nicotinamide adenine dinucleotide (NAD$^+$), is a derivative of ADP and the vitamin nicotinamide (see **Figure 22.22**). The reactive site of NAD$^+$ is located in the nicotinamide portion of the molecule. During the oxidation of a substrate, the nicotinamide ring of NAD$^+$ accepts two electrons and one proton, which forms the reduced coenzyme NADH.



NAD$^+$
(oxidized form)

NADH
(reduced form)

(22.9)

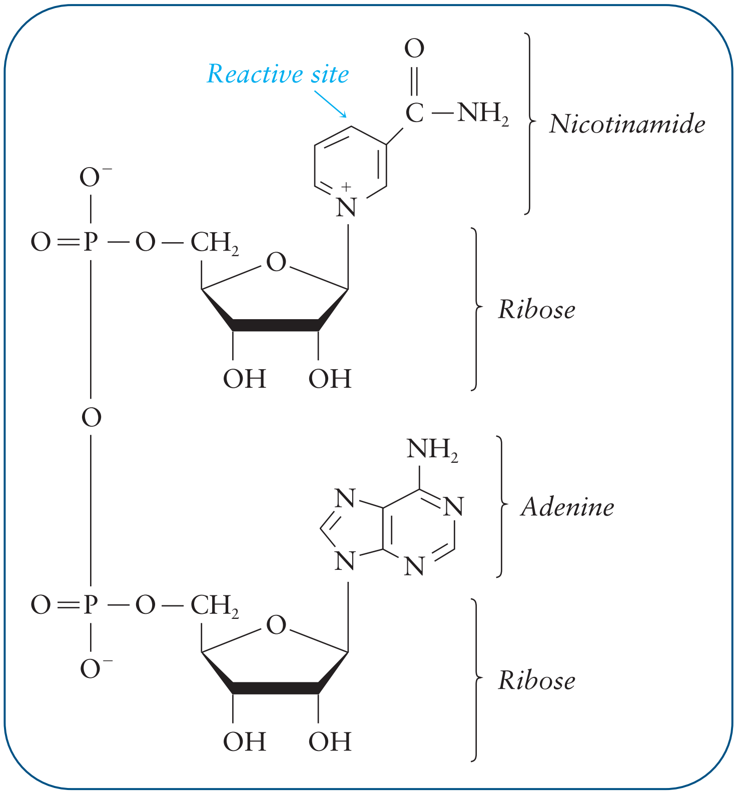
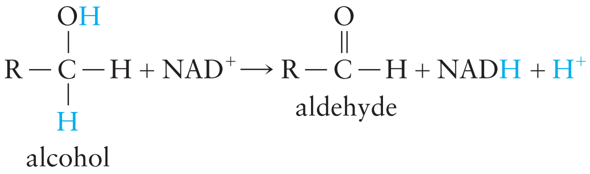


FIGURE 22.22 The structure of nicotinamide adenine dinucleotide (NAD^+). The reactive site is in the nicotinamide part of the molecule.

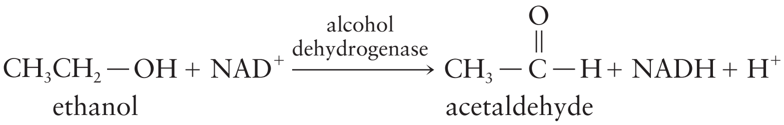
A typical cellular reaction in which NAD^+ serves as an electron acceptor is the oxidation of an alcohol:

General reaction:



$$\underset{\text{alcohol}}{R-\overset{OH}{\underset{H}{\overset{|}{\underset{|}{C}}}}-H} + NAD^+ \longrightarrow \underset{\text{aldehyde}}{R-\overset{O}{\overset{\|}{C}}-H} + NADH + H^+ \qquad (22.10)$$

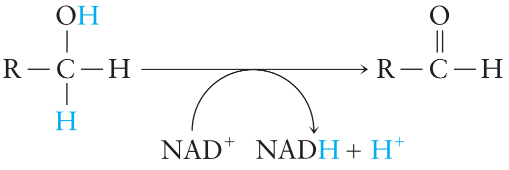
Specific example:



$$\underset{\text{ethanol}}{CH_3CH_2-OH} + NAD^+ \xrightarrow[\text{dehydrogenase}]{\text{alcohol}} \underset{\text{acetaldehyde}}{CH_3-\overset{O}{\overset{\|}{C}}-H} + NADH + H^+ \qquad (22.11)$$

In this reaction, one hydrogen atom of the alcohol substrate is directly transferred to NAD^+, whereas the other appears in solution as H^+. Both electrons lost by the alcohol have been transferred to the nicotinamide ring in NADH.

Biochemical reactions in which coenzymes participate are often written in a more concise way. For example, Reaction 22.10 may be written:

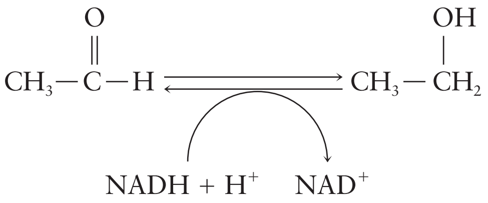


$$R-\overset{OH}{\underset{H}{\overset{|}{\underset{|}{C}}}}-H \xrightarrow[NAD^+ \quad NADH + H^+]{} R-\overset{O}{\overset{\|}{C}}-H \qquad (22.12)$$

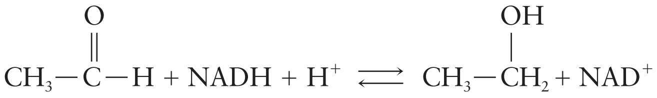
This format allows for the separate emphasis of the oxidation reaction and the involvement of a coenzyme.

Example 22.5 Writing Coenzyme Reactions

Write the following reaction in the normal form of a chemical equation:

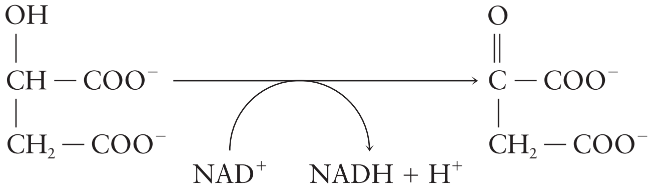


Solution



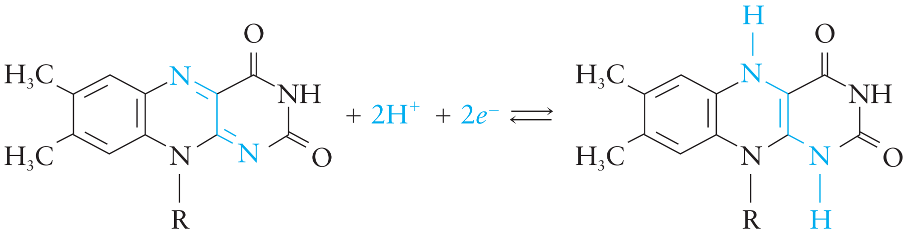
$$CH_3-\overset{O}{\overset{\|}{C}}-H + NADH + H^+ \rightleftarrows CH_3-\overset{OH}{\overset{|}{C}}H_2 + NAD^+$$

✔ LEARNING CHECK 22.5 Write the following reaction in the normal form of a chemical equation:



Flavin adenine dinucleotide (FAD) is the other major electron carrier in the oxidation of fuel molecules. This coenzyme is a derivative of ADP and the vitamin riboflavin. The reactive site is located within the riboflavin ring system (see **Figure 22.23**).

As in the reduction of NAD$^+$, substrates of enzymes that use FAD as the coenzyme give up two electrons to the coenzyme. However, unlike NAD$^+$, the FAD coenzyme accepts both of the hydrogen atoms lost by the substrate. Thus, the abbreviation for the reduced form of FAD is FADH$_2$:



(22.13)

FAD
(oxidized form)

FADH$_2$
(reduced form)

HEALTH CONNECTIONS 22.2

Fiber Supplements?

Added fiber is popping up in everything these days, including yogurt, ice cream, nutrition bars, cookies, juice, and even water. The health benefits of fiber are numerous and include promoting bowel health and regularity, cholesterol and blood sugar reduction, and increasing satiety, which can help with weight control. The recommended daily intake of fiber ranges between 25 and 38 grams per day, yet most Americans consume only about 12 grams per day. So, fiber-fortified foods or supplements could help us narrow the gap—right?

One problem with this idea is that added fibers, such as those found in many supplements or used to fortify foods, might not have the same health benefits as naturally occurring, or intact, fiber. Added fiber generally comes in the form of isolated fibers, which include inulin, polydextrose, and maltrodextrin. Naturally occurring fiber-rich foods like whole grains, beans, fruits, nuts, seeds, and vegetables contain a variety of fiber types, often in a combination of water-soluble and insoluble fiber. These foods also contain vitamins, minerals, and phytonutrients, but isolated fibers offer only one type of fiber without the accompanying nutrients.

Fiber supplements vary in the types of fiber that they contain. Psyllium, a naturally occurring soluble fiber, has been studied extensively, and research suggests a benefit in terms of constipation prevention, cholesterol reduction, blood sugar control, and weight loss, particularly when combined with a healthy diet. It also seems to help those suffering from irritable bowel syndrome (IBS), a common condition associated with bowel irregularity, bloating, and abdominal pain.

There is no question that obtaining fiber directly from regular foods is optimal, but there are some cases in which a supplement or fortified food might be helpful. However, more research is needed to determine the health benefits of isolated fibers. Simply adding a fiber supplement to an unhealthy diet is much less beneficial than changing the diet to include more healthful foods.

iStock.com/Jaimie D. Travis

Naturally occurring fiber-rich foods include whole grains, nuts, and seeds.

Sorin Popa/Shutterstock.com

Fiber supplements may have certain health benefits.

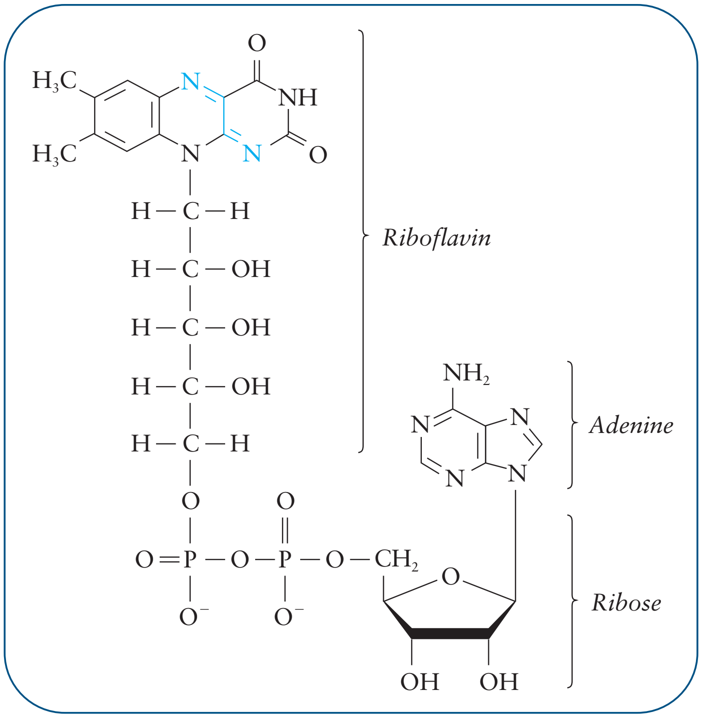
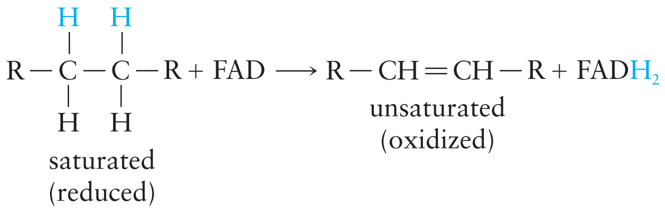


FIGURE 22.23 The structure of flavin adenine dinucleotide (FAD). The reactive portion (shown in blue) is in the riboflavin ring system.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

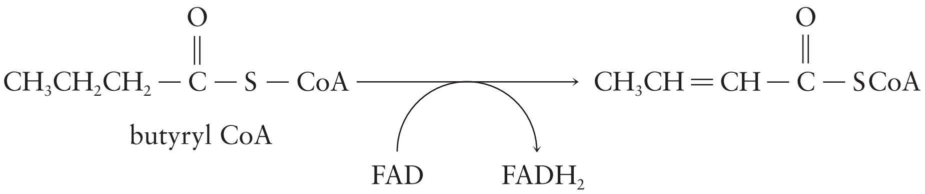
The substrates for oxidation reactions in which FAD is the coenzyme differ from those involving NAD^+. FAD is often involved in oxidation reactions in which a $—CH_2—CH_2—$ portion of the substrate is oxidized to a double bond:

General reaction:



$$\underset{\text{saturated (reduced)}}{R-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-R} + FAD \longrightarrow \underset{\text{unsaturated (oxidized)}}{R-CH=CH-R} + FADH_2 \qquad (22.14)$$

Specific example:

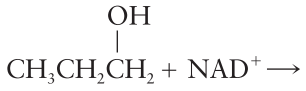


$$\underset{\text{butyryl CoA}}{CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-S-CoA} \xrightarrow[FAD \qquad FADH_2]{} CH_3CH=CH-\overset{O}{\overset{\|}{C}}-SCoA \qquad (22.15)$$

Example 22.6 More Writing Coenzyme Reactions

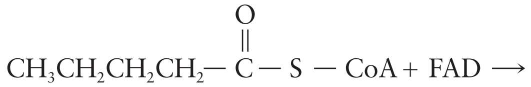
Complete the following reactions:

a.



$$CH_3CH_2\overset{OH}{\overset{|}{C}H_2} + NAD^+ \longrightarrow$$

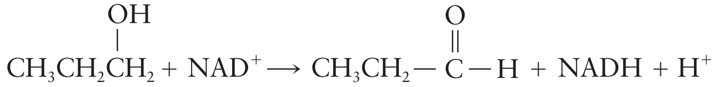
b.



$$CH_3CH_2CH_2CH_2-\overset{O}{\overset{\|}{C}}-S-CoA + FAD \longrightarrow$$

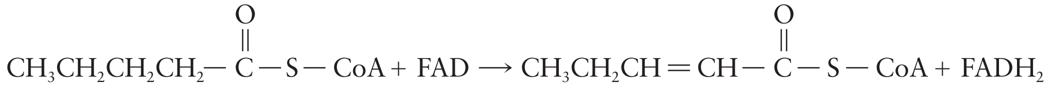
Solution

a.



$$CH_3CH_2\overset{OH}{\overset{|}{C}H_2} + NAD^+ \longrightarrow CH_3CH_2-\overset{O}{\overset{\|}{C}}-H + NADH + H^+$$

b.

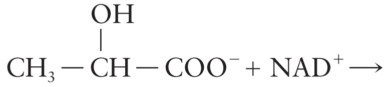


$$CH_3CH_2CH_2CH_2-\overset{O}{\overset{\|}{C}}-S-CoA + FAD \longrightarrow CH_3CH_2CH=CH-\overset{O}{\overset{\|}{C}}-S-CoA + FADH_2$$

✔ **LEARNING CHECK 22.6** Complete the following reactions:

a. $^-OOC-CH_2-CH_2-COO^- + FAD \longrightarrow$

b.



$$CH_3-\overset{OH}{\overset{|}{C}H}-COO^- + NAD^+ \longrightarrow$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Health Career Description

NUTRITIONIST/NUTRITION THERAPIST

The requirements to become a nutritionist vary from state to state. However, in most locations, nutritionists must complete a bachelor's degree, perform a certain amount of supervised, hands-on training, and pass a licensing examination. Nutrition therapists provide education and support to the community or individuals in areas of diet analysis and planning for the purpose of creating and supporting healthy lifestyles that result in healthy weight management for individuals and management of chronic diseases. They often take on a role similar to a life coach, as a counselor with a focus on nutrition. They analyze existing diets, create individualized diet plans, support individuals in implementing diet changes, and educate individuals and groups on the importance of nutrition for health.

Many universities now offer bachelor or even master's degrees in nutrition. Weber State University in Ogden, Utah describes their Integrative Nutrition program as follows.

> Integrative Nutrition includes nutrition as it intersects with other related fields to support health and wellbeing of individuals and groups.
>
> The Integrative Nutrition Educator graduate will have demonstrated competence and knowledge in diet analysis and design, fitness nutrition, lifespan nutrition, sustainable cooking, and related exercise science, health, child and family studies, botany, microbiology, physical education, recreation, and/or psychology topics with cultural application and sensitivity.

Common reasons that clients seek help from nutrition therapists include assistance with weight loss, diabetes management, nutrition support during chemotherapy, help with eating disorders, nutrition guidance during pregnancy or lactation, and nutrition support for exercise and sports regimens.

Nutritionists work closely with people and are expected to have good communication and organizational skills, as well as the ability to understand the complexities of human physiology, psychology, organic chemistry, and pharmacology.

Concept Summary

22.1 Nutritional Requirements

Learning Objective: Can you describe the difference between macronutrients and micronutrients in terms of amounts required and their functions in the body?

- Every human body requires certain amounts of various macronutrients and micronutrients, water, and fiber to function properly.
- The amounts needed vary with a number of factors such as body size, age, and sex.
- Various countries have established nutritional guidelines in attempts to maintain good health for their citizens.
- In the United States, the Reference Daily Intakes (RDIs) and Daily Reference Values (DRVs) are designed to represent appropriate nutrient intake for 95% of the population.

22.2 The Macronutrients

Learning Objective: Can you describe the primary functions in the body of each macronutrient?

- Macronutrients are substances required by the body in relatively large amounts.
- They are used by the body to provide energy and the materials necessary to form new or replacement tissue.
- The macronutrients are carbohydrates, lipids, and proteins.
- An RDI has been established only for proteins, but other groups have recommended the amounts of carbohydrates, lipids, and proteins that should be included in the diet.

22.3 Micronutrients I: Vitamins

Learning Objective: Can you distinguish between and classify vitamins as water-soluble or fat-soluble on the basis of name and behavior in the body?

- Vitamins are organic micronutrients that the body cannot produce in the amounts needed for good health.
- A number of vitamins have high water solubility resulting from the highly polar nature of their molecules.
- All but one of the water-soluble vitamins are known to function as coenzymes in the body and are involved in many important metabolic processes.
- Fat-soluble vitamins have nonpolar molecular structures.
- As a result, they are insoluble in water but soluble in fat or other nonpolar solvents.
- Fat-soluble vitamins act somewhat like hormones in the body.
- Fat-soluble vitamins do not dissolve in water-based body fluids, so they are not excreted through the kidneys.
- Amounts in excess of bodily requirements are stored in body fat.
- Thus, it is much easier to produce toxic effects by overdosing with fat-soluble vitamins than with water-soluble vitamins.

22.4 Micronutrients II: Minerals

Learning Objective: Can you list a primary function in the body for each major mineral?

- Minerals are inorganic substances needed by the body.
- Those present in the body in amounts equal to or greater than 5 grams are called major minerals.
- Those present in smaller amounts are called trace minerals.
- Minerals perform many useful functions in the body.

22.5 The Flow of Energy in the Biosphere

Learning Objective: Can you describe the major steps in the flow of energy in the biosphere?

- Energy for all living processes comes from the sun.
- A portion of the sun's energy is trapped in the process of photosynthesis, which produces carbohydrates.
- We derive energy from the foods we eat: carbohydrates, lipids and proteins.
- As these substances are oxidized, molecules of ATP that supply the energy needed for cellular processes are formed.

22.6 Metabolism and an Overview of Energy Production

Learning Objective: Can you differentiate among metabolism, anabolism and catabolism? Can you outline the three stages in the extraction of energy from food?

- Metabolism, the sum of all cellular reactions, involves the breakdown (catabolism) and synthesis (anabolism) of molecules.
- There are three stages in the catabolism of foods to provide energy.
- In Stage I, digestion converts foods into smaller molecules.
- In Stage II, these smaller molecules are converted into two-carbon acetyl units that combine with coenzyme A, forming acetyl CoA.
- Stage III, which is called the common catabolic pathway, consists of the citric acid cycle followed by the electron transport chain and oxidative phosphorylation.
- The main function of catabolism is to produce ATP molecules.

22.7 ATP: The Primary Energy Carrier

Learning Objective: Can you explain how ATP plays a central role in the production and use of cellular energy?

- Molecular ATP is the link between energy production and energy use in cells.
- ATP is called a high-energy compound because of the large amount of free energy liberated on hydrolysis.
- Cells are able to harness the free energy liberated by ATP to carry out cellular work.
- ATP is consumed immediately following its formation and is quickly regenerated from ADP as fuel molecules are oxidized.
- Mitochondria play a key role in energy production because they house the enzymes for both the citric acid cycle and the electron transport chain.

22.8 Important Coenzymes in the Common Catabolic Pathway

Learning Objective: Can you explain the role of coenzymes in the common catabolic pathway?

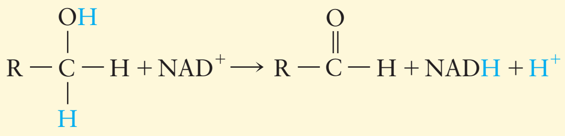
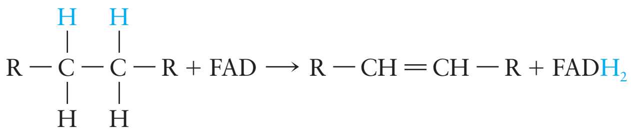
- Three very important coenzymes are involved in catabolism: coenzyme A, NAD^+, and FAD.
- Coenzyme A binds to the two-carbon fragments produced in Stage II to form acetyl CoA, the direct fuel of the citric acid cycle.
- NAD^+ and FAD are the oxidizing agents that participate in the oxidation reactions of the citric acid cycle.
- They transport hydrogen atoms and electrons from the citric acid cycle to the electron transport chain.

Key Terms and Concepts

Anabolism (22.6)
Catabolism (22.6)
Cellular respiration (22.5)
Common catabolic pathway (22.6)
Complete protein (22.2)
Complex carbohydrates (22.2)
Daily Reference Values (DRVs) (22.1)
Daily Values (DVs) (22.1)
Essential amino acid (22.2)
High-energy compound (22.7)
Macronutrient (22.1)
Major mineral (22.4)
Metabolic pathway (22.6)
Metabolism (22.6)
Micronutrient (22.1)
Mineral (22.4)
Mitochondrion (22.7)
Nutrition (Introduction)
Reference Daily Intakes (RDIs) (22.1)
Satiety (22.2)
Simple carbohydrates (22.2)
Thioester bond (22.8)
Trace mineral (22.4)

Key Equations

1. Photosynthesis (**Section 22.5**):	$6CO_2 + 6H_2O + \text{energy} \rightarrow C_6H_{12}O_6 \rightarrow 6O_2$	Reaction 22.2
2. Hydrolysis of ATP (**Section 22.7**):	$ATP + H_2O \rightarrow ADP + P_i + H^+$	Reaction 22.5

3. Oxidation by NAD$^+$ (**Section 22.8**):	 $\mathrm{R-\underset{H}{\overset{OH}{C}}-H + NAD^+ \longrightarrow R-\overset{O}{\overset{\|}{C}}-H + NADH + H^+}$	Reaction 22.10
5. Oxidation by FAD (**Section 22.8**):	 $\mathrm{R-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-R + FAD \longrightarrow R-CH{=}CH-R + FADH_2}$	Reaction 22.14

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Nutritional Requirements (Section 22.1)

22.1 What is the principal component of dietary fiber?

22.2 What is the primary difference between a macronutrient and a micronutrient?

22.3 Calculate how many mg of sodium per day are recommended in a 2000-cal/day diet using the "Amount per serving" and "% Daily Value" information supplied in **Figure 22.2.**

22.4 Using your answer to Exercise 22.3 calculate the number of teaspoons of salt that would be needed to fulfill the daily requirements if one level teaspoon of salt contains 4250 mg of sodium.

22.5 Calculate how many grams of Total Carbohydrate are recommended in a 2000-cal/day diet using the "Amount per serving" and "% Daily Value" information supplied in **Figure 22.2**.

22.6 Using your answer to Exercise 22.5, calculate the number of average-sized (150 g) potatoes you would have to eat to fulfill the daily requirements if one potato contains 26 g of Total Carbohydrate.

22.7 Calculate how many grams of Dietary Fiber are recommended in a 2000-cal/day diet using the "Amount per serving" and "% Daily Value" information supplied in **Figure 22.2**.

22.8 Using your answer to Exercise 22.7, calculate the number of average-sized (150 g) potatoes you would have to eat to fulfill the daily requirements if one potato contains 2 g of Dietary Fiber.

22.9 Explain the importance of sufficient fiber in the diet.

The Macronutrients (Section 22.2)

22.10 List two general functions in the body for each of the macronutrients.

22.11 For each of the following macronutrients, list a single food item that would be a good source:

a. Carbohydrate (simple) **c.** Lipid

b. Carbohydrate (complex) **d.** Protein

22.12 Identify the class of macronutrient (carbohydrates, lipids, proteins, or more than one class) being characterized by each of the following statements.

a. Can be defined as simple or complex.

b. Only macronutrient with RDIs for different groups of people.

c. Are digested more slowly than other macronutrients.

d. Are triglycerides.

22.13 Identify the class of macronutrient (carbohydrates, lipids, proteins, or more than one class) being characterized by each of the following statements.

a. Can be defined as saturated or unsaturated.

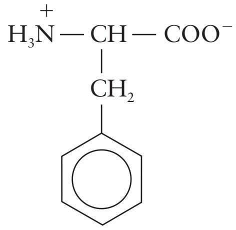
b. Are natural polymers of amino acids.

c. Has components that are considered essential.

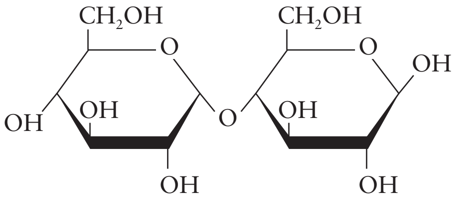
d. Includes the category called "fiber."

22.14 Identify the class of macronutrient (carbohydrate, lipid, or protein) to which each of the following belongs.

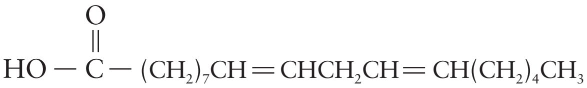
a.



b.

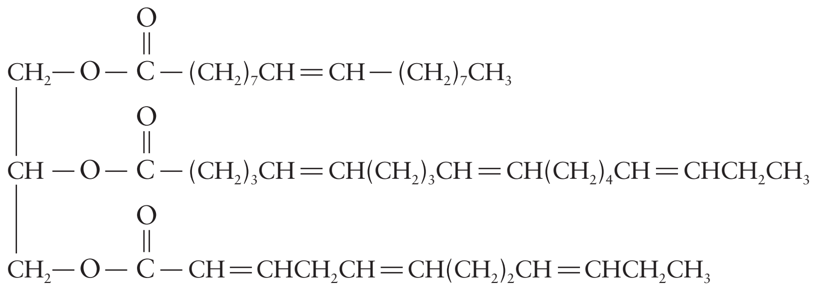


c.

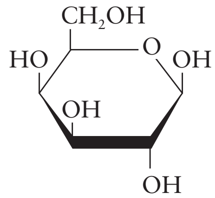


$\mathrm{HO-\overset{O}{\overset{\|}{C}}-(CH_2)_7CH{=}CHCH_2CH{=}CH(CH_2)_4CH_3}$

22.15 Identify the class of macronutrient (carbohydrate, lipid, or protein) to which each of the following belongs.

a. 

b. **Ala — Trp — Arg — Ser — Cys — Gln**

c. 

22.16 List the types of macronutrients found in each of the following food items. List the nutrients in approximate decreasing order of abundance (most abundant first, etc.).

a. Potato chips

b. Buttered toast

c. Plain toast with jam

d. Cheese sandwich

22.17 List the types of macronutrients found in each of the following food items. List the nutrients in approximate decreasing order of abundance (most abundant first, etc.).

a. A lean steak

b. A fried egg

c. Boiled broccoli

d. Chicken noodle soup

22.18 Why is linoleic acid called an essential fatty acid for humans?

22.19 Use **Figure 22.2** and list the Daily Values (DV) for fat, saturated fat, total carbohydrate, and fiber based on a 2000-calorie diet.

22.20* Use the Daily Values (DVs) given in **Figure 22.2** to calculate the number of calories in a 2000-calorie diet that should be from fat, saturated fat, and total carbohydrate. Proteins and carbohydrates provide about 4 calories/gram. Fats provide about 9 calories/gram.

Micronutrients I: Vitamins (Section 22.3)

22.21 Identify each of the following vitamins as water-soluble or fat-soluble.

a. Tocopherol

b. Niacin

c. Folic acid

d. Retinol

22.22 Identify each of the following vitamins as water-soluble or fat-soluble.

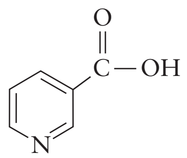
a. Calciferol

b. Biotin

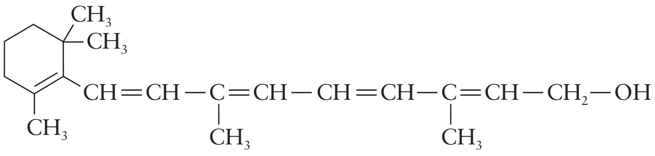
c. Thiamin

d. Cobalamin

22.23 Based on its structure, would you expect the vitamin below to be water-soluble or fat-soluble? Explain your answer.



22.24 Based on its structure, would you expect the vitamin below to be water-soluble or fat-soluble? Explain your answer.



22.25 What general function is served by eight of the water-soluble vitamins?

22.26 Why is there more concern about large doses of fat-soluble vitamins than of water-soluble vitamins?

22.27 What fat-soluble vitamin deficiency is associated with the following?

a. Night blindness

b. Blood clotting

c. Calcium and phosphorus use in forming bones and teeth

d. Preventing oxidation of fatty acids

22.28 What water-soluble vitamin deficiency is associated with the following?

a. Scurvy

b. Beriberi

c. Pernicious anemia

d. Pellagra

Micronutrients II: Minerals (Section 22.4)

22.29 What is the difference between a vitamin and a mineral?

22.30 List at least one specific function for each major mineral of the body.

22.31 What determines whether a mineral is classified as a major or trace mineral?

22.32 Using information supplied in **Table 22.4**, explain why many sports drinks contain sodium chloride (NaCl) and potassium chloride (KCl).

22.33 What are the general functions of trace minerals in the body?

22.34 To help prevent iodine deficiencies, many table salts are iodized by adding potassium iodate (KIO_3) to the salt (NaCl). Explain why potassium iodate and not iodine (I_2) is added to make iodized salt.

22.35 How can the ingestion of a small lump of elemental sodium metal be toxic when sodium is a required major mineral?

The Flow of Energy in the Biosphere (Section 22.5)

22.36 What element serves as a fuel for the fusion process occurring on the sun?

22.37 What is the source of energy for life on Earth?

22.38 Write a net equation for the photosynthetic process.

22.39 Photosynthesis changes light energy to energy found in chemical bonds. Explain why some scientists consider photosynthesis as the most important chemical reaction that occurs on Earth, as far as life is concerned.

22.40 Explain how Earth's supply of carbon compounds may be recycled by the processes of photosynthesis and respiration.

22.41 Explain the difference between cellular respiration and pulmonary respiration.

22.42 Explain how some of the carbon atoms you ate in your hamburger for lunch today may have once been inside an apatosaur 150 million years ago.

22.43 Describe in general terms the steps in the flow of energy from the sun to molecules of ATP.

Metabolism and an Overview of Energy Production (Section 22.6)

22.44 What is a metabolic pathway?

22.45 Classify catabolism and anabolism as synthetic or breakdown processes.

22.46 Classify catabolism and anabolism as energy-producing or energy-consuming processes.

22.47 Is photosynthesis catabolic or anabolic? Give two reasons why.

22.48 Is cellular respiration catabolic or anabolic? Give two reasons why.

22.49 Outline the three stages in the extraction of energy from food.

22.50 Which stage of energy production is concerned primarily with the following?

- **a.** Formation of ATP
- **b.** Digestion of fuel molecules
- **c.** Consumption of O_2
- **d.** Generation of acetyl CoA

22.51 Which stage of energy production is concerned primarily with the following?

- **a.** Produces carbon dioxide
- **b.** Macronutrient components degraded into two-carbon units
- **c.** Uses oxygen to make water
- **d.** Hydrolysis of macronutrients

22.52 Explain why Stage III of energy production is referred to as the common catabolic pathway.

22.53 In terms of energy production, what is the main purpose of the catabolic pathway?

22.54 Would the digestion of protein to amino acids that are then used to build muscle in the body be considered a catabolic pathway? Why or why not?

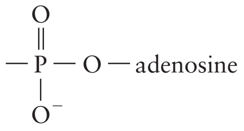
ATP: The Primary Energy Carrier (Section 22.7)

22.55 Is ATP involved in anabolic processes or catabolic processes?

22.56 What do the symbols ATP, ADP, and AMP represent?

22.57 Explain why ATP is referred to as the primary energy carrier.

22.58 Using the partial structure shown below, write the structure of ATP, ADP, and AMP:



$$-\overset{\overset{\displaystyle O}{\|}}{\underset{\underset{\displaystyle O^-}{|}}{P}}-O-\text{adenosine}$$

22.59 What do the symbols P_i and PP_i represent?

22.60 Using symbolic formulas such as ADP and PP_i, write equations for the hydrolysis of ATP to ADP and the hydrolysis of ATP to AMP.

22.61 Using **Table 22.5**, explain why phosphoenolpyruvate is called a high-energy compound but glycerol-3-phosphate is not.

22.62 Using **Table 22.5**, identify which compound in each of the following pairs releases more energy upon hydrolysis.

- **a.** ATP and phosphoenolpyruvate
- **b.** Phosphocreatine and ADP
- **c.** Glucose-1-phosphate and 1,3-bisphosphoglycerate
- **d.** AMP and glycerol-3-phosphate

22.63 Using **Table 22.5**, identify which compound in each of the following pairs releases more energy upon hydrolysis.

- **a.** ATP and phosphocreatine
- **b.** Glucose-1-phosphate and glucose-6-phosphate
- **c.** ADP and AMP
- **d.** Phosphoenolpyruvate and carbomoyl phosphate

22.64 What does the symbol $\Delta G^{\circ\prime}$ represent? How does the sign for $\Delta G^{\circ\prime}$ indicate whether a reaction is exergonic or endergonic?

22.65 Which portion of the ATP molecule is particularly responsible for it being described as a high-energy compound?

22.66 In general, would you expect an anabolic process to have an overall $+\Delta G°'$ or a $-\Delta G°'$ value? Explain your answer.

22.67 In general, would you expect a catabolic process to have an overall $+\Delta G°'$ or a $-\Delta G°'$ value? Explain your answer.

22.68 Why is it more accurate to refer to ATP as a carrier or donor of free energy rather than as a storage form of free energy?

22.69 What is the role of mitochondria in the use of energy by living organisms?

22.70 Describe the importance and function of the ATP–ADP cycle.

22.71 Describe the structure of a mitochondrion and identify the location of enzymes important in energy production.

Important Coenzymes in the Common Catabolic Pathway (Section 22.8)

22.72 What coenzymes are produced by the body from the following vitamins?

a. Riboflavin **b.** Pantothenic acid **c.** Nicotinamide

22.73 What roles do the following coenzymes serve in the catabolic oxidation of foods?

a. Coenzyme A **b.** FAD **c.** NAD^+

22.74 Write the abbreviations for the oxidized and reduced forms of:

a. Flavin adenine dinucleotide

b. Nicotinamide adenine dinucleotide

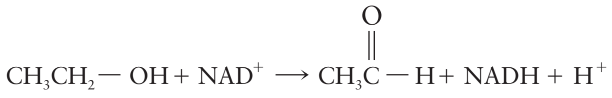
22.75* Which compound is oxidized in the following reaction? Which compound is reduced?

$$^-OOC-CH_2-CH_2-COO^- + FAD \longrightarrow {}^-OOC-CH{=}CH-COO^- + FADH_2$$

22.76 Would you expect $NAD^+ + 2e^- + H^+ \rightarrow NADH$ to have a $+\Delta G°'$ or a $-\Delta G°'$? Explain your answer.

22.77 Would you expect $FADH_2 \rightarrow FAD + 2H^+ + 2e^-$ to have a $+\Delta G°'$ or a $-\Delta G°'$? Explain your answer.

22.78 Which compound is oxidized in the following reaction? Which compound is reduced?



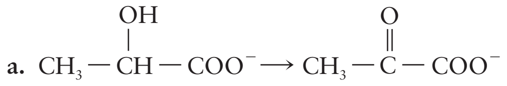
$$CH_3CH_2-OH + NAD^+ \longrightarrow CH_3\overset{\overset{\displaystyle O}{\|}}{C}-H + NADH + H^+$$

22.79* Write balanced reactions for the following oxidations using NAD^+ or FAD:

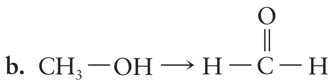
a. $HO-CH_2-COOH \rightarrow O{=}CH-COOH$

b. $HO-CH_2CH_2-OH \rightarrow HO-CH{=}CH-OH$

22.80 Write balanced reactions for the following oxidations using NAD^+:



a. $CH_3-\overset{\overset{\displaystyle OH}{|}}{CH}-COO^- \longrightarrow CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-COO^-$



b. $CH_3-OH \longrightarrow H-\overset{\overset{\displaystyle O}{\|}}{C}-H$

22.81 Draw abbreviated structural formulas to show the reactive portion of FAD and the reduced compound $FADH_2$.

22.82 Draw abbreviated structural formulas to show the reactive portion of NAD^+ and the reduced compound NADH.

Additional Exercises

22.83 Based on the solubility characteristics of vitamin B_1, would you expect to find it in the interior of an enzyme or on the exterior surface of the enzyme when it acts as a coenzyme?

22.84 Balance the following equation. How many electrons will be transferred to NADH?

$$CH_4 + O_2 + \_\_\_\_ NAD^+ \rightarrow CO_2 + \_\_\_\_ NADH + \_\_\_\_ H^+$$

22.85 Draw an energy diagram that depicts the two hydrolysis reactions of ATP below.

$$ATP \rightarrow ADP + P_i \rightarrow AMP + 2P_i$$

22.86 What would be the main process in the human body that would be interrupted by a deficiency of an essential amino acid? What specific part of that process would be affected?

22.87 Average 18-year-olds should get 1300 mg of calcium in their diet daily. Use **Figure 22.10** and calculate the percentage of the daily intake that represents the total amount of calcium found in a 60-kg person.

Chemistry for Thought

22.88 At one time, a system of MDR (minimum daily requirement) values for nutrients was used. Why do you think Daily Values (DVs) might be more informative and useful than MDRs?

22.89 Briefly explain why you think it would be undesirable or beneficial (decide which position to defend in each case) to follow a diet that is (a) extremely low in carbohydrates, (b) extremely low in lipids, or (c) extremely low in proteins.

22.90 Doughnuts, even those without frosting, are high in triglycerides. Explain.

22.91 One of the oils listed in **Figure 22.6** is palm oil, which for several years was used in fast-food restaurants to fry potatoes. Why was this use considered an unhealthy practice?

22.92 In **Figure 22.7**, it is observed that vegetables are a source of protein. We most often think of meats, grains, and dairy products as sources of protein, but not vegetables. Use **Table 19.4** to list the types of protein that might be found in vegetables.

22.93 Vitamin tablets and oranges are both plentiful sources of vitamin C. Why might an orange be better for you than taking a vitamin C tablet?

22.94 A cold cereal manufactured from corn is deficient in the amino acid lysine. What other foods in a breakfast meal might supply lysine?

22.95 The body has a storage capacity for excess carbohydrates and fats but not for excess proteins. What consequences does this fact have for a daily diet?

22.96 Which macronutrient is a major source of dietary sulfur?

23 Carbohydrate Metabolism

Monkey Business Images/Shutterstock.com

Health Career Focus

SONOGRAPHER

I could hardly believe it when the doctor told me I had gestational diabetes! During pregnancy, some women cannot metabolize carbohydrates and sugars very well. This can lead to problems in both the mother and baby. It seems unfair that other women eat whatever they want during pregnancy, but I have to be so careful!

One thing motivates me to stick to the diet—when I see my baby during ultrasound exams. With the high quality "4D ultrasound," we get an amazing view of the baby. My partner and I look forward to those appointments so much!

The ultrasound technicians are very friendly and professional. They take time to obtain the needed measurements, but they also work hard to get good pictures of the baby's face and to explain any confusing images—they explain everything—and take plenty of time to answer our questions.

I feel empowered to do anything for my baby (including limiting carbs!) when I see that sweet little face on the monitor!

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Identify the products of carbohydrate digestion. **(Section 23.1)**
2. Explain the importance to the body of maintaining proper blood sugar levels. **(Section 23.2)**
3. List the starting material and products of the glycolysis pathway. **(Section 23.3)**
4. Describe how the glycolysis pathway is regulated in response to cellular needs. **(Section 23.3)**
5. Name the three fates of pyruvate. **(Section 23.4)**
6. Identify the two major functions of the citric acid cycle. **(Section 23.5)**
7. Describe how the citric acid cycle is regulated in response to cellular energy needs. **(Section 23.5)**
8. Explain the function of the electron transport chain and describe how electrons move down the chain. **(Section 23.6)**
9. List the major features of the chemiosmotic hypothesis. **(Section 23.7)**
10. Calculate the amount of ATP produced by the complete oxidation of a mole of glucose. **(Section 23.8)**

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

11 Explain the importance of the processes of glycogenesis and glycogenolysis. **(Section 23.9)**

12 Describe gluconeogenesis and the operation of the Cori cycle. **(Section 23.10)**

13 Describe how hormones regulate carbohydrate metabolism. **(Section 23.11)**

CARBOHYDRATES PLAY MAJOR roles in cell metabolism. The central substance in carbohydrate metabolism is glucose; it is the key food molecule for most organisms. As the major carbohydrate metabolic pathways are discussed, you will see that each one involves either the use or the synthesis of glucose. You will also see how the chemical degradation of glucose provides energy in the cell, how glucose is stored, how the blood glucose level is regulated, and how diabetes results from changes in blood glucose regulation mechanisms.

23.1 The Digestion of Carbohydrates

Learning Objective 1 Identify the products of carbohydrate digestion.

The major function of dietary carbohydrates is to serve as an energy source (see **Figure 23.1**). In a typical American diet, carbohydrates meet about 45–55% of the daily energy needs. Fats and proteins furnish the remaining energy. During carbohydrate digestion, di- and polysaccharides are hydrolyzed to monosaccharides, primarily glucose, fructose, and galactose:

$$\text{polysaccharides} + H_2O \xrightarrow{\text{digestion}} \text{glucose} \tag{23.1}$$

$$\text{sucrose} + H_2O \xrightarrow{\text{digestion}} \text{glucose} + \text{fructose} \tag{23.2}$$

$$\text{lactose} + H_2O \xrightarrow{\text{digestion}} \text{glucose} + \text{galactose} \tag{23.3}$$

$$\text{maltose} + H_2O \xrightarrow{\text{digestion}} \text{glucose} \tag{23.4}$$

New Africa/Shutterstock.com

FIGURE 23.1 Carbohydrates are a major source of energy for human activity.

After digestion is completed, glucose, fructose, and galactose are absorbed into the bloodstream through the lining of the small intestine and transported to the liver. In the liver, fructose and galactose are rapidly converted to glucose or to compounds that are metabolized by the same pathway as glucose.

23.2 Blood Glucose

Learning Objective 2 Explain the importance to the body of maintaining proper blood sugar levels.

Glucose is by far the most plentiful monosaccharide found in blood, and the term *blood sugar* usually refers to glucose. In adults, the normal **blood sugar level** measured after a fast of 8–12 hours is in the range of 70–110 mg/100 mL. (In clinical reports, such levels are often expressed in units of milligrams per deciliter, mg/dL.) The blood sugar level reaches a maximum of approximately 140–160 mg/100 mL about 1 hour after a carbohydrate-containing meal. It returns to normal after 2–2½ hours.

blood sugar level The amount of glucose present in blood, normally expressed as milligrams per 100 mL of blood.

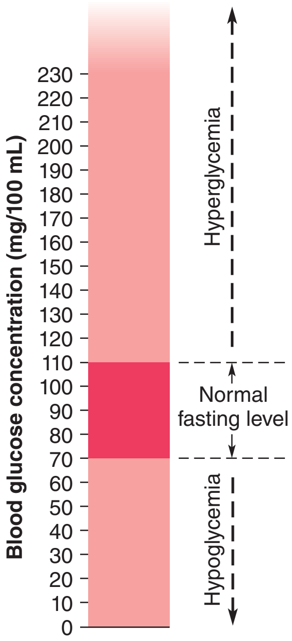


FIGURE 23.2 Blood glucose levels.

hypoglycemia A lower-than-normal blood sugar level.

hyperglycemia A higher-than-normal blood sugar level.

renal threshold The blood glucose level at which glucose begins to be excreted in the urine.

glucosuria A condition in which elevated blood sugar levels result in the excretion of glucose in the urine.

glycolysis A series of reactions by which glucose is oxidized to pyruvate.

If a blood sugar level is below the normal fasting level, a condition called **hypoglycemia** exists. Because glucose is the only nutrient normally used by the brain for energy, mild hypoglycemia leads to dizziness and fainting as brain cells are deprived of energy. Severe hypoglycemia can cause convulsions and coma. When the blood glucose concentration is above normal, the condition is referred to as **hyperglycemia**. If blood glucose levels exceed approximately 180 mg/100 mL, the sugar is not completely reabsorbed by the kidneys, and glucose is excreted in the urine (see **Figure 23.2**). The blood glucose level at which this occurs is called the **renal threshold**, and the condition in which glucose appears in the urine is called **glucosuria**. Prolonged hyperglycemia at a glucosuric level must be considered serious because it indicates that something is wrong with the body's normal ability to control the blood sugar level.

The liver is the key organ involved in regulating the blood glucose level. The liver responds to the increase in blood glucose that follows a meal by removing glucose from the bloodstream. The removed glucose is primarily converted to glycogen or triglycerides for storage. Similarly, when blood glucose levels are low, the liver responds by converting stored glycogen to glucose and by synthesizing new glucose from noncarbohydrate substances.

23.3 Glycolysis

Learning Objective 3 List the starting material and products of the glycolysis pathway.

Learning Objective 4 Describe how the glycolysis pathway is regulated in response to cellular needs.

Glycolysis is an important part of the catabolic process by which the body gets energy from carbohydrates. It consists of a series of 10 reactions, with the net result being the conversion of a glucose molecule into two molecules of pyruvate. All enzymes for glycolysis are present in the cellular cytoplasm. The 10 reactions of glycolysis catalyzed by these enzymes are represented in **Figure 23.3**. The addition of all these reactions gives a net reaction for glycolysis:

$$\text{glucose} + 2\text{P}_i + 2\text{ADP} + 2\text{NAD}^+ \rightarrow 2\text{ pyruvate} + 2\text{ATP} + 2\text{NADH} + 4\text{H}^+ + 2\text{H}_2\text{O} \qquad (23.5)$$

This equation indicates a net gain of 2 mol of ATP for every mole of glucose converted to pyruvate. In addition, 2 mol of the coenzyme NADH is formed when NAD^+ serves as an oxidizing agent in glycolysis. Fructose and galactose from digested food are both converted into intermediates that enter into the glycolysis pathway. Fructose enters glycolysis as dihydroxyacetone phosphate and glyceraldehyde-3-phosphate, whereas galactose is metabolized to glucose and enters in the form of glucose-6-phosphate.

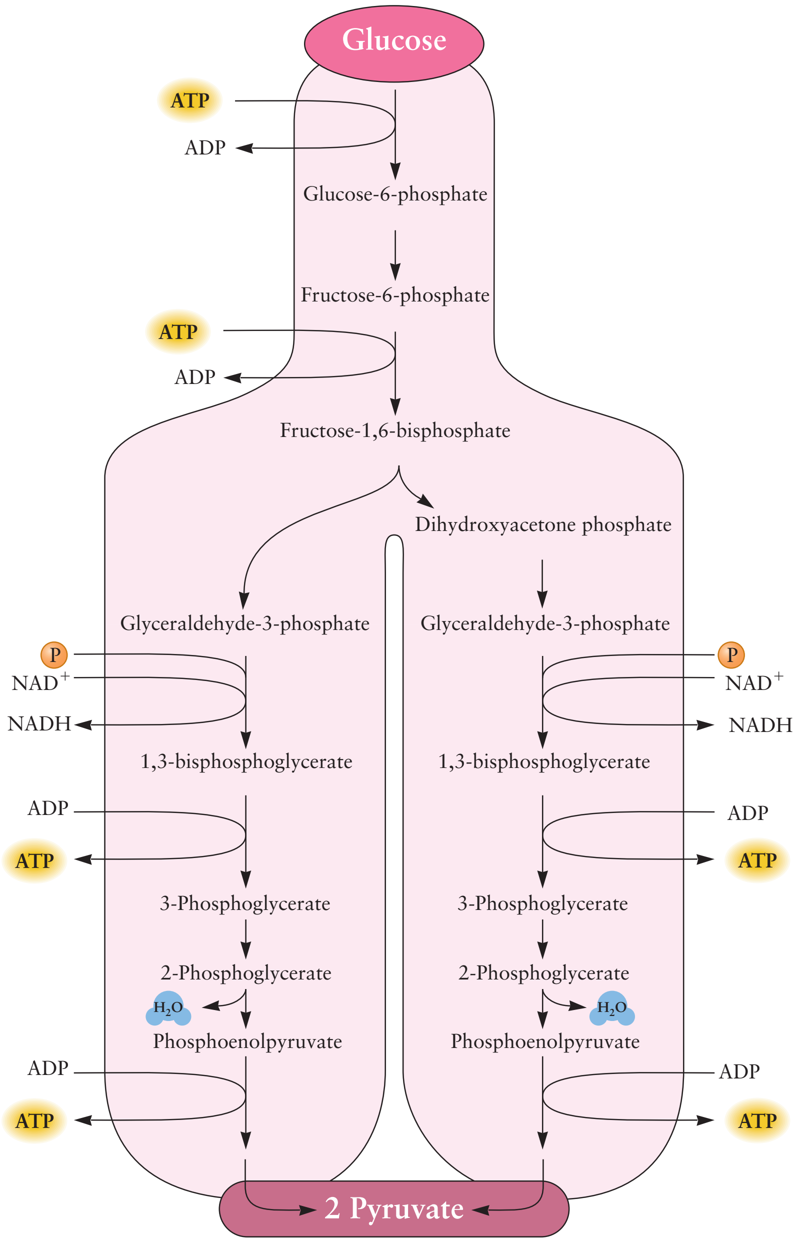
23.3A The Regulation of Glycolysis

The glycolysis pathway, like all metabolic pathways, is controlled constantly. The precise regulation of the concentrations of pathway intermediates is efficient and makes possible the rapid adjustment of the output level of pathway products as the need arises.

The glycolysis pathway is regulated by three enzymes: hexokinase, phosphofructokinase, and pyruvate kinase. The regulation of the pathway is shown in **Figure 23.4**.

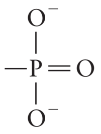
Hexokinase catalyzes the conversion of glucose to glucose-6-phosphate and thus initiates the glycolysis pathway. The enzyme is inhibited by a high concentration of glucose-6-phosphate, the product of the reaction it catalyzes. Thus, the phosphorylation of glucose is controlled by feedback inhibition (see **Section 20.8**).

A second and very important control point for glycolysis shown in **Figure 23.4** is the step catalyzed by phosphofructokinase. Once glucose is converted to fructose-1,6-bisphosphate, its carbon skeleton must continue through the glycolytic pathway. The phosphorylation of fructose-6-phosphate is a committed step that will occur as long as the enzyme is active. As an allosteric enzyme (**Section 20.8**), phosphofructokinase is inhibited by high concentrations of ATP and citrate, and it is activated by high concentrations of ADP and AMP.


Glucose
ATP
ADP
Glucose-6-phosphate
Fructose-6-phosphate
ATP
ADP
Fructose-1,6-bisphosphate
Dihydroxyacetone phosphate
Glyceraldehyde-3-phosphate
Glyceraldehyde-3-phosphate
P
NAD+
NADH
P
NAD+
NADH
1,3-bisphosphoglycerate
1,3-bisphosphoglycerate
ADP
ATP
ADP
ATP
3-Phosphoglycerate
3-Phosphoglycerate
2-Phosphoglycerate
2-Phosphoglycerate
H2O
H2O
Phosphoenolpyruvate
Phosphoenolpyruvate
ADP
ATP
ADP
ATP
2 Pyruvate

From *Biochemistry, 5th Edition* by Campbell & Farrell. © 2006 Thomson Higher Education

FIGURE 23.3 A summary of glycolysis. The Ⓟ stands for



$$-\overset{\overset{\displaystyle O^-}{|}}{\underset{\underset{\displaystyle O^-}{|}}{P}}=O$$

and the prefix "bis-" is used to denote two of these groups.

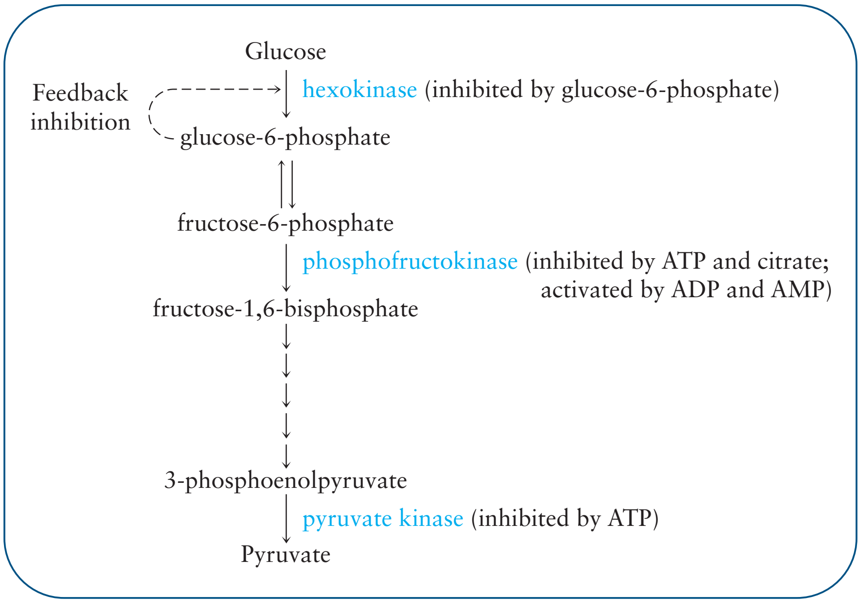

Glucose
Feedback inhibition
hexokinase (inhibited by glucose-6-phosphate)
glucose-6-phosphate
fructose-6-phosphate
phosphofructokinase (inhibited by ATP and citrate; activated by ADP and AMP)
fructose-1,6-bisphosphate
3-phosphoenolpyruvate
pyruvate kinase (inhibited by ATP)
Pyruvate

FIGURE 23.4 The regulation of the glycolysis pathway. Glucose-6-phosphate is a noncompetitive inhibitor of hexokinase. Phosphofructokinase and pyruvate kinase are also allosteric enzymes subject to control.

HEALTH CONNECTIONS **23.1**

How Can We Avoid Energy Crashes?

An “energy crash” typically occurs 1 to 3 hours after a meal, usually late morning, after breakfast, and early afternoon, after lunch. The term *energy crash* is not scientific, but is generally used to indicate a rapid drop in blood sugar that is accompanied by symptoms including headaches, hunger, decreased ability to concentrate, and even mood changes. The reason for the rapid decline in blood sugar is usually related to the nutrient content of the previous meal. For example, meals containing large amounts of rapidly digested carbohydrates can cause a rapid increase in blood sugar. The blood sugar increase leads to a surge in the release of insulin, a hormone that transfers sugar from the blood to cells of the brain or muscles for use as energy, or to fat cells for storage. Thus, a quick spike in blood sugar, leading to an exaggerated release of insulin, can cause a fairly rapid drop in blood sugar, which in turn causes symptoms of an energy crash.

The measure of how quickly and significantly a specific food increases blood sugar levels is known as the glycemic index (GI) of the food. The GI is obtained by comparing the total increase in blood sugar during the two hours following the consumption of a sample of the food that contains 50 grams of carbohydrate. This increase is compared to the increase caused by a control that generally consists of the consumption of 50 grams of glucose, which has a GI of 100. Foods with generally high GI values include refined grains, white potatoes, white rice, white bread, sugary cereals, candy, baked goods, crackers, pretzels, fruit drinks, and sodas.

The glycemic index of a meal can be decreased in several ways. Consuming lower GI carbohydrates like whole grains, oats, whole-grain cereals and breads, brown rice, and beans instead of refined grains, sugary cereals, white rice, and white potatoes is key. Opting for fiber-rich whole fruit instead of juice is helpful, and limiting the intake of sugary beverages, snacks, baked goods, and candy is important. Finally, combining healthy fat or lean protein with carbohydrates at each meal also helps lower the GI of the meal. By lowering the GI of meals, blood sugar levels remain more constant throughout the day, helping you avoid energy crashes.

iStock.com/nkbimages

Sugary foods have high GI values.

The third control point is the last step of glycolysis, the conversion of phosphoenolpyruvate to pyruvate catalyzed by pyruvate kinase. This enzyme, too, is an allosteric enzyme that is inhibited by higher concentrations of ATP.

To understand how these controls interact, remember that when the glycolysis pathway is operating at a maximum rate, so also are the citric acid cycle and the electron transport chain. As a result of their activity, large quantities of ATP are produced. The entire pathway continues to operate at a high rate, as long as the produced ATP is used up by processes within the cell. However, if ATP use decreases, the concentration of ATP increases, and more diffuses to the binding sites of the allosteric enzymes sensitive to ATP. Thus, the activity of these enzymes decreases. When phosphofructokinase is inhibited in this way, the entire glycolysis pathway slows or stops. As a result, the concentration of glucose-6-phosphate increases, thus inhibiting hexokinase and the initial step of the glycolysis pathway.

Conversely, when ATP concentrations are low, the concentrations of AMP and ADP are high. The AMP and ADP function as activators (**Section 20.8**) that influence phosphofructokinase and thereby speed up the entire glycolysis pathway.

Example 23.1 Regulating Glycolysis

Identify the three control points in the glycolysis pathway by listing the reactions involved.

Solution

Glucose → glucose-6-phosphate
Fructose → fructose-1,6-bisphosphate
3-phosphoenolpyruvate → pyruvate

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

✔ **LEARNING CHECK 23.1** Explain how each of the following enzymes helps regulate the glycolysis pathway:

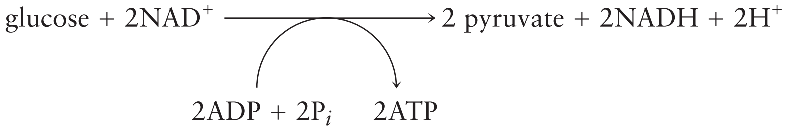
a. hexokinase
b. phosphofructokinase
c. pyruvate kinase

23.4 The Fates of Pyruvate

Learning Objective 5 Name the three fates of pyruvate.

The sequence of reactions that converts glucose to pyruvate is very similar in all organisms and in all kinds of cells. However, the fate of the pyruvate as it is used to generate energy is variable. Three different fates of pyruvate are considered here.

As glucose is oxidized to pyruvate in glycolysis, NAD^+ is reduced to NADH. The need for a continuous supply of NAD^+ for glycolysis is a key to understanding the fates of pyruvate.



$$\text{glucose} + 2\text{NAD}^+ \xrightarrow[2\text{ADP} + 2\text{P}_i \quad 2\text{ATP}]{} 2\text{ pyruvate} + 2\text{NADH} + 2\text{H}^+$$

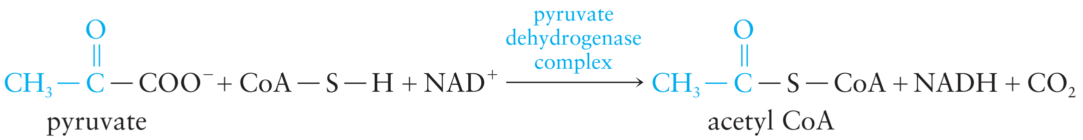
(23.6)

In each case, pyruvate is metabolized in ways that regenerate NAD^+ so that glycolysis can continue.

23.4A Oxidation to Acetyl CoA

The mitochondrial membrane is permeable to pyruvate formed by glycolysis in the cytoplasm, and under **aerobic** conditions (a plentiful oxygen supply), pyruvate is converted inside the mitochondria to acetyl CoA.

aerobic In the presence of oxygen.



$$\underset{\text{pyruvate}}{\text{CH}_3-\overset{\text{O}}{\overset{\|}{\text{C}}}-\text{COO}^-} + \text{CoA}-\text{S}-\text{H} + \text{NAD}^+ \xrightarrow{\text{pyruvate dehydrogenase complex}} \underset{\text{acetyl CoA}}{\text{CH}_3-\overset{\text{O}}{\overset{\|}{\text{C}}}-\text{S}-\text{CoA}} + \text{NADH} + \text{CO}_2$$

(23.7)

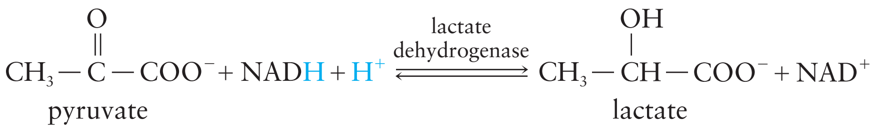
Acetyl CoA formed in this reaction can enter the citric acid cycle on its way to complete oxidation to CO_2. The NAD^+ needed for the conversion of pyruvate to acetyl CoA (Reaction 23.7) and for the operation of the glycolysis pathway (Step 6) is regenerated when NADH transfers its electrons to O_2 in the electron transport chain.

Not all acetyl CoA generated metabolically enters the citric acid cycle. Some also serve as a starting material for fatty acid biosynthesis (**Section 24.7**). The fatty acid components of triglycerides, for example, are synthesized using acetyl CoA. Thus, as most people are aware, the intake of excess dietary carbohydrates can lead to an increase in body fat storage.

23.4B Reduction to Lactate

Under **anaerobic** conditions, such as those that accompany strenuous or long-term muscle activity, the cellular supply of oxygen is not adequate for the reoxidation of NADH to NAD^+. Under such conditions, the cells begin reducing pyruvate to lactate as a means of regenerating NAD^+:

anaerobic In the absence of oxygen.



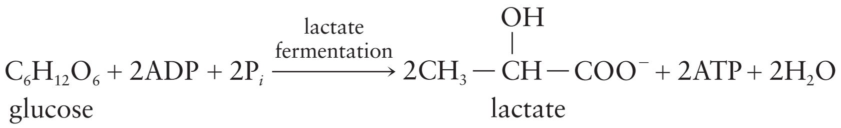
$$\underset{\text{pyruvate}}{\text{CH}_3-\overset{\text{O}}{\overset{\|}{\text{C}}}-\text{COO}^-} + \text{NADH} + \text{H}^+ \xrightleftharpoons{\text{lactate dehydrogenase}} \underset{\text{lactate}}{\text{CH}_3-\overset{\text{OH}}{\overset{|}{\text{CH}}}-\text{COO}^-} + \text{NAD}^+$$

(23.8)

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

lactate fermentation The production of lactate from glucose.

When Reaction 23.8 is added to the net reaction of glycolysis, an overall reaction for **lactate fermentation** results:



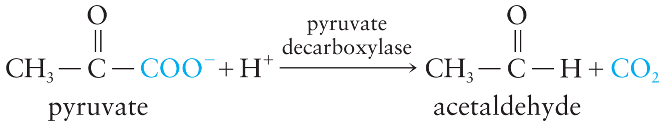
$$\underset{\text{glucose}}{\mathrm{C_6H_{12}O_6}} + 2\mathrm{ADP} + 2\mathrm{P}_i \xrightarrow{\substack{\text{lactate}\\ \text{fermentation}}} 2\mathrm{CH_3}-\underset{\text{lactate}}{\overset{\mathrm{OH}}{\overset{|}{\mathrm{CH}}}-\mathrm{COO^-}} + 2\mathrm{ATP} + 2\mathrm{H_2O} \qquad (23.9)$$

Notice that the NAD$^+$ produced when pyruvate is reduced (Reaction 23.8) is used up and does not appear in lactate fermentation (Reaction 23.9). Although much more energy is available from the complete oxidation of pyruvate under aerobic conditions, the two ATPs produced from lactate fermentation are sufficient to sustain the life of anaerobic microorganisms. In human metabolism, those two molecules of ATP also play a critical role by furnishing energy when cellular supplies of oxygen are insufficient for ATP production through the complete oxidation of pyruvate.

23.4C Reduction to Ethanol

alcoholic fermentation The conversion of glucose to ethanol.

Several organisms, including yeast, have developed an alternative pathway for the regeneration of NAD$^+$ under anaerobic conditions. The process, called **alcoholic fermentation**, involves the decarboxylation of pyruvate to form acetaldehyde:



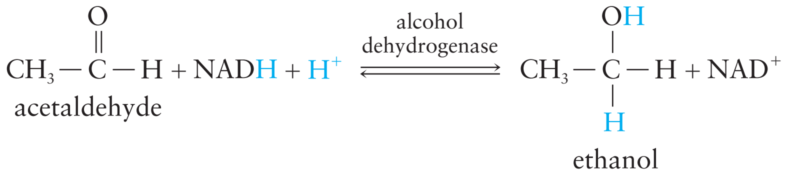
$$\underset{\text{pyruvate}}{\mathrm{CH_3}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{COO^-}} + \mathrm{H^+} \xrightarrow{\substack{\text{pyruvate}\\ \text{decarboxylase}}} \underset{\text{acetaldehyde}}{\mathrm{CH_3}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{H}} + \mathrm{CO_2} \qquad (23.10)$$

Maxim Khytra/Shutterstock.com

FIGURE 23.5 Bread, wine, and cheese are all produced through fermentation processes.

The carbon dioxide produced in this reaction causes beer to foam and provides carbonation for naturally fermented wines and champagnes (see **Figure 23.5**).

The second step in alcoholic fermentation is the reduction of acetaldehyde to ethanol by NADH:



$$\underset{\text{acetaldehyde}}{\mathrm{CH_3}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{H}} + \mathrm{NADH} + \mathrm{H^+} \underset{}{\overset{\substack{\text{alcohol}\\ \text{dehydrogenase}}}{\rightleftharpoons}} \underset{\text{ethanol}}{\mathrm{CH_3}-\underset{\mathrm{H}}{\underset{|}{\overset{\mathrm{OH}}{\overset{|}{\mathrm{C}}}}}-\mathrm{H}} + \mathrm{NAD^+} \qquad (23.11)$$

The NAD$^+$ regenerated by this reaction may then be used in the glycolysis pathway.

An overall reaction for alcoholic fermentation is obtained by combining the reaction for the conversion of pyruvate to ethanol and the reactions of glycolysis. Notice that because NAD$^+$ is used up in glycolysis but regenerated in ethanol formation, it does not appear in the overall equation:

$$\underset{\text{glucose}}{\mathrm{C_6H_{12}O_6}} + 2\mathrm{ADP} + 2\mathrm{P}_i \xrightarrow{\substack{\text{alcoholic}\\ \text{fermentation}}} \underset{\text{ethanol}}{2\mathrm{CH_3CH_2}-\mathrm{OH}} + 2\mathrm{CO_2} + 2\mathrm{ATP} \qquad (23.12)$$

Figure 23.6 summarizes the various pathways pyruvate can follow as it is used to regenerate NAD$^+$.

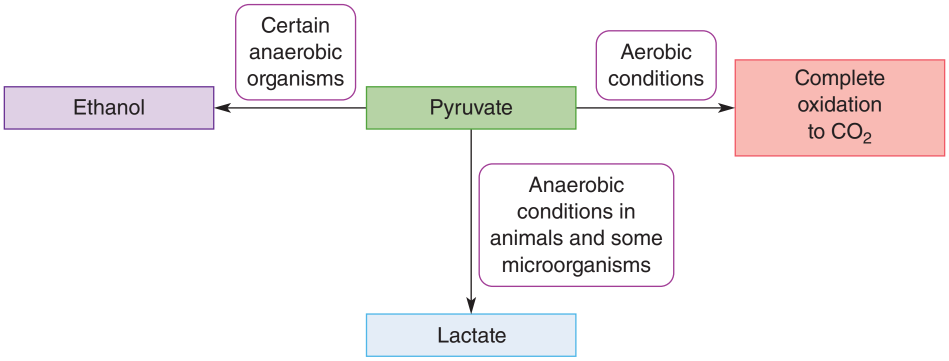

Certain anaerobic organisms
Ethanol
Pyruvate
Aerobic conditions
Complete oxidation to CO$_2$
Anaerobic conditions in animals and some microorganisms
Lactate

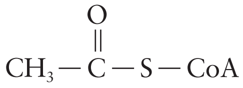
FIGURE 23.6 The fates of pyruvate.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Example 23.2 Describing the Fates of Pyruvate

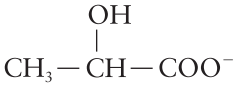
Write structures for the three fates (products) of pyruvate.

Solution



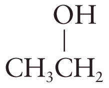
$$CH_3-\overset{\overset{O}{\|}}{C}-S-CoA$$

acetyl CoA



$$CH_3-\overset{\overset{OH}{|}}{CH}-COO^-$$

lactate



$$CH_3\overset{\overset{OH}{|}}{CH_2}$$

ethanol

✔ **LEARNING CHECK 23.2** Why is it important that each biochemical fate of pyruvate involve the production of NAD$^+$?

23.5 The Citric Acid Cycle

Learning Objective 6 Identify the two major functions of the citric acid cycle.

Learning Objective 7 Describe how the citric acid cycle is regulated in response to cellular energy needs.

Stage III in the oxidation of fuel molecules (see **Section 22.6**) begins when the two-carbon acetyl units (of acetyl CoA) enter the **citric acid cycle**. This process is called the citric acid cycle because one of the key intermediates is citric acid. However, it is also called the tricarboxylic acid cycle (TCA) in reference to the three carboxylic acid groups in citric acid, and the Krebs cycle in honor of Sir Hans A. Krebs, who deduced its reaction sequence in 1937 (see **Figure 23.7**).

citric acid cycle A series of reactions in which acetyl CoA is oxidized to carbon dioxide and reduced forms of coenzymes FAD and NAD$^+$ are produced.

The citric acid cycle is the principal process for generating the reduced coenzymes NADH and FADH$_2$, which are necessary for the reduction of oxygen and ATP synthesis in the electron transport chain. Another important function of the citric acid cycle as a source of intermediates for biosynthesis is discussed in **Section 24.11**.

Bettmann/Getty Images

FIGURE 23.7 Sir Hans Adolf Krebs (1900–1981), German-born British biochemist, received the 1953 Nobel Prize in physiology or medicine.

23.5A Reactions of the Citric Acid Cycle

The reactions of the citric acid cycle occur within the matrix of the mitochondrion. **Figure 23.8** summarizes the details of the eight reactions that make up the citric acid cycle. Of particular importance are those reactions in which molecules of NADH and FADH$_2$ are produced. Notice that a two-carbon unit (the acetyl group) enters the cycle and that two carbon atoms are liberated in the form of two CO$_2$ molecules, one each in Reactions 3 and 4. Thus, this series of reactions both begins and ends with a C$_4$ compound, oxaloacetate. This is why the pathway is called a cycle. In each trip around the cycle, the starting material is regenerated and the reactions can proceed again as long as more acetyl CoA is available as fuel.

23.5B A Summary of the Citric Acid Cycle

The individual reactions of the cycle can be added to give an overall net equation:

$$\begin{aligned}&\text{acetyl CoA} + 3NAD^+ + FAD + GDP + P_i + 2H_2O \rightarrow \\ &\qquad 2CO_2 + CoA{-}S{-}H + 3NADH + 2H^+ + FADH_2 + GTP \qquad (23.13)\end{aligned}$$

Some important features of the citric acid cycle are the following:

1. Acetyl CoA, available from the breakdown of carbohydrates, lipids, and amino acids, is the fuel of the citric acid cycle.
2. The operation of the cycle requires a supply of the oxidizing agents NAD$^+$ and FAD. The cycle is dependent on reactions of the electron transport chain to supply the necessary NAD$^+$ and FAD (**Section 23.6**). Because oxygen is the final acceptor of electrons in the electron transport chain, the continued operation of the citric acid cycle depends ultimately on an adequate supply of oxygen.

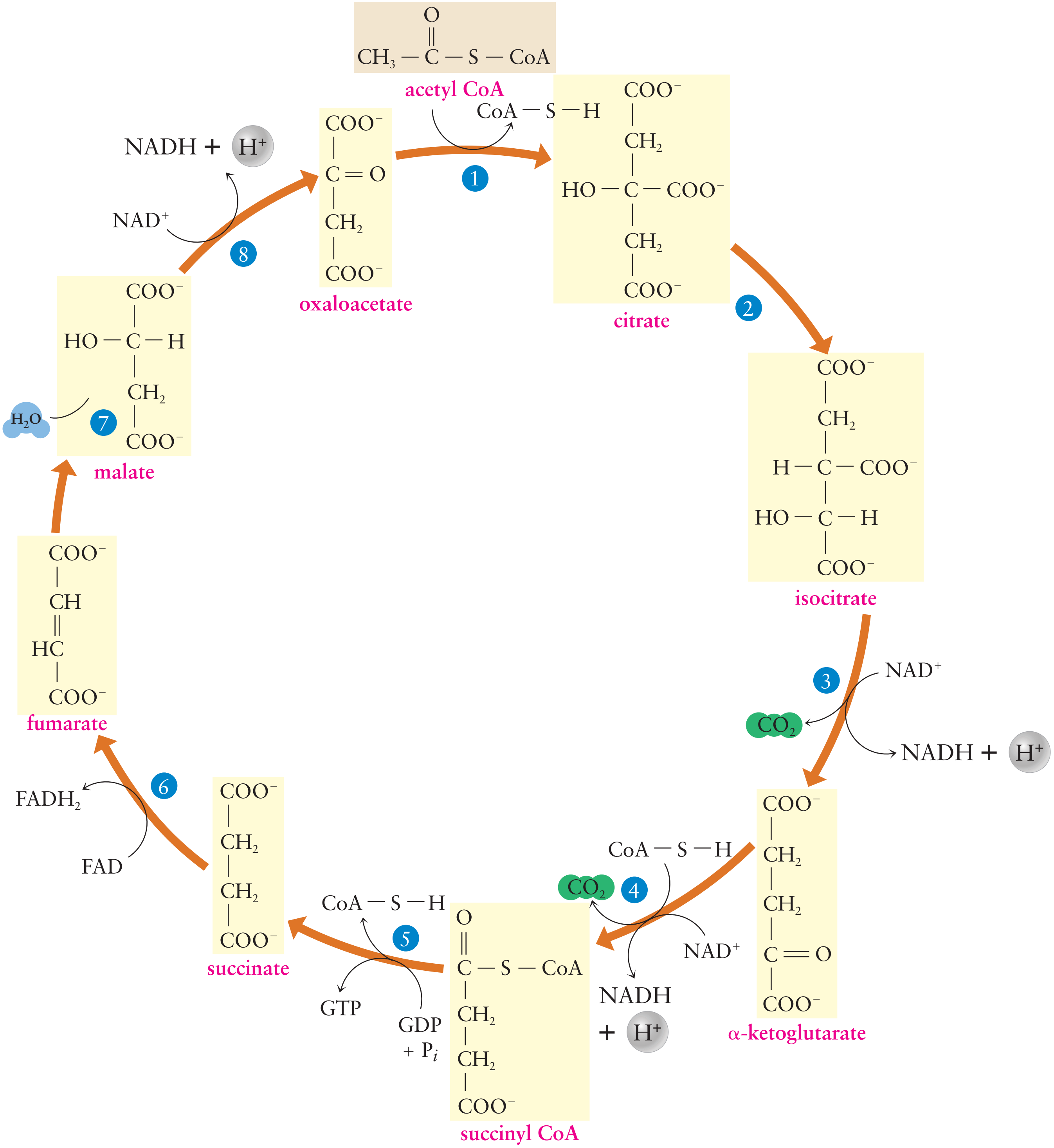

acetyl CoA
CoA — S — H
1
citrate
2
isocitrate
3
NAD+
CO_2
NADH + H+
α-ketoglutarate
CoA — S — H
CO_2
4
NAD+
NADH + H+
succinyl CoA
CoA — S — H
5
GTP
GDP + P_i
succinate
6
$FADH_2$
FAD
fumarate
H_2O
7
malate
NAD+
8
NADH + H+
oxaloacetate

FIGURE 23.8 The citric acid cycle.

3. Two carbon atoms enter the cycle as an acetyl unit, and two carbon atoms leave the cycle as two molecules of CO_2. However, the carbon atoms leaving the cycle correspond to carbon atoms that entered in the previous cycle; there is a one-cycle delay between the entry of two carbon atoms as an acetyl unit and their release as CO_2.
4. In each complete cycle, four oxidation–reduction reactions produce three molecules of NADH and one molecule of $FADH_2$.
5. One molecule of the high-energy phosphate compound guanosine triphosphate (GTP) (see **Section 22.7**) is generated.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

HEALTH CONNECTIONS 23.2

Lactate Accumulation

During vigorous exercise, the oxygen supply to muscles can become too low to support increased aerobic conversion of pyruvate to acetyl CoA. Under such conditions, a shift occurs from aerobic pyruvate oxidation to anaerobic production of lactate as the means for producing ATP. The resulting accumulation of lactate causes the muscle pain and cramps that accompany physical exhaustion. The buildup of lactate also causes a slight decrease in blood pH, which triggers an increase in the rate and depth of breathing, a response that provides more oxygen to the cells. The combination of pain from lactate accumulation and the maximum rate of breathing represents a limit to physical activities. Regular training and exercise increase this limit by improving the efficiency with which oxygen is delivered to the cells. The muscle cells of a well-conditioned athlete can maintain the aerobic oxidation of pyruvate for a much longer period of activity than can those of a nonathlete.

The shift to anaerobic lactate formation also occurs in the heart muscle during an episode of cardiac arrest, in which the oxygen-carrying blood supply to the heart is cut off by the blockage of an artery leading to the heart muscles. Aerobic oxidation of pyruvate and its ATP production are stopped. Glycolysis proceeds at an accelerated rate to meet the energy needs, and lactate accumulates. The heart muscle contracts, producing a cramp, and stops beating. Massaging the heart muscle relieves such cramps, just as it does for skeletal muscles. Thus, it is sometimes possible to start the heart beating by massaging it.

Premature infants, whose lungs are not fully developed, are given pure oxygen to breathe in order to prevent a shift to anaerobic lactate production. In addition, they are given bicarbonate solutions intravenously to combat the increasing acidity of the blood due to lactate buildup.

KVG
JAKO
NAGYATÁD

muzsy/Shutterstock.com

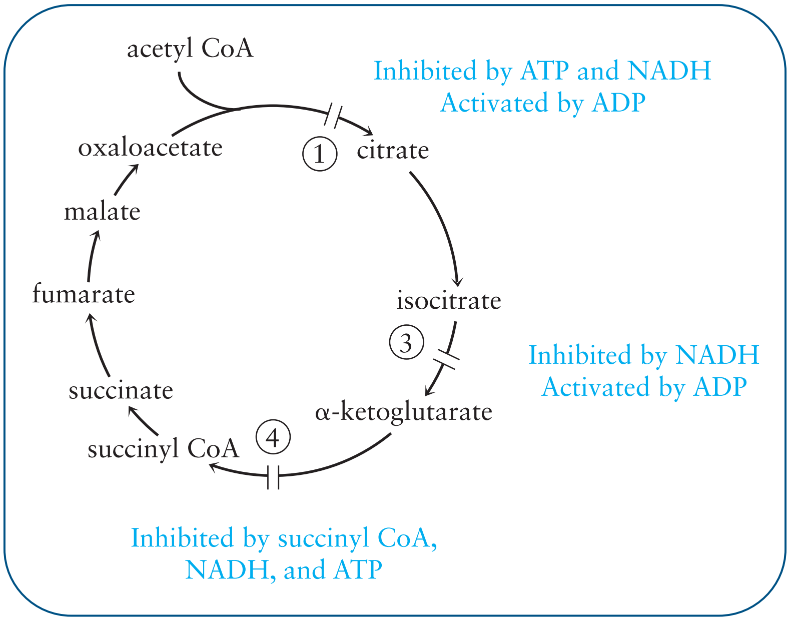
Vigorous exercise causes a buildup of lactate in tissues.

23.5C Regulation of the Citric Acid Cycle

The rate at which the citric acid cycle operates is precisely adjusted to meet cellular needs for ATP. One important control point is the very first step in the cycle, the synthesis of citrate. The catalyst for this reaction, citrate synthetase, is an allosteric enzyme that is inhibited by ATP and NADH and activated by ADP. When cellular needs for ATP are met, ATP interacts with citrate synthetase and reduces its affinity for acetyl CoA. Thus, ATP acts as a modulator (inhibitor) of citrate synthetase and inhibits the entry of acetyl CoA into the citric acid cycle. Similarly, NADH acts as an inhibitor and signals the citric acid cycle to slow the production of NADH and $FADH_2$. On the other hand, when ATP levels are low, ADP levels are usually high. ADP, an activator of citrate synthetase, stimulates the entry of acetyl CoA into the citric acid cycle and thus boosts the production of NADH and $FADH_2$.

Isocitrate dehydrogenase (Reaction 3), a second controlling enzyme, is an allosteric enzyme that is activated by ADP and inhibited by NADH in very much the same way as is citrate synthetase. The third control point (Reaction 4) is catalyzed by the α-ketoglutarate dehydrogenase complex. This group of enzymes is inhibited by succinyl CoA and NADH, products of the reaction it catalyzes, and also by ATP. These control points are indicated in **Figure 23.9**. In short, the entry of acetyl CoA into the citric acid cycle and the rate at which the cycle operates are reduced when cellular ATP levels are high. When ATP supplies are low (and ADP levels are high), the cycle is stimulated.

FIGURE 23.9 Control points in the citric acid cycle.



Example 23.3 Regulating the Citric Acid Cycle

Identify the three control points in the citric acid cycle by listing the reactions involved.

Solution

Oxaloacetate + acetyl CoA → citrate

Isocitrate → α-ketoglutarate → succinyl CoA

✔ **LEARNING CHECK 23.3** Explain how ADP serves to regulate the citric acid cycle and thus the production of ATP.

23.6 The Electron Transport Chain

Learning Objective 8 Explain the function of the electron transport chain and describe how electrons move down the chain.

The reduced coenzymes NADH and $FADH_2$ are end products of the citric acid cycle. In the final stage of food oxidation, the hydrogen ions and electrons carried by these coenzymes combine with oxygen and form water.

$$4H^+ + 4e^- + O_2 \rightarrow 2H_2O \qquad (23.14)$$

electron transport chain A series of reactions in which protons and electrons from the oxidation of foods are used to reduce molecular oxygen to water.

This simple energy-releasing process does not take place in a single step. Instead, it occurs in a series of steps that involve a number of enzymes and cofactors located within the inner membrane of the mitochondria. Electrons from the reduced coenzymes are passed from one electron carrier to another within the membrane in assembly-line fashion and are finally combined with molecular oxygen, the final electron acceptor. The series of reactions involved in the process is called the **electron transport chain**. As illustrated in **Figure 23.10**, there are several intermediate electron carriers between NADH and molecular oxygen. The electron carriers are lined up in order of increasing affinity for electrons.

The first electron carrier in the electron transport chain is an enzyme that contains a tightly bound coenzyme. The coenzyme has a structure similar to FAD. The enzyme formed by the combination of this coenzyme with a protein is called flavin mononucleotide (FMN). Two electrons and one H^+ ion from NADH plus another H^+ ion from a mitochondrion pass to FMN, then to an iron–sulfur (Fe—S) protein, and then to coenzyme

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

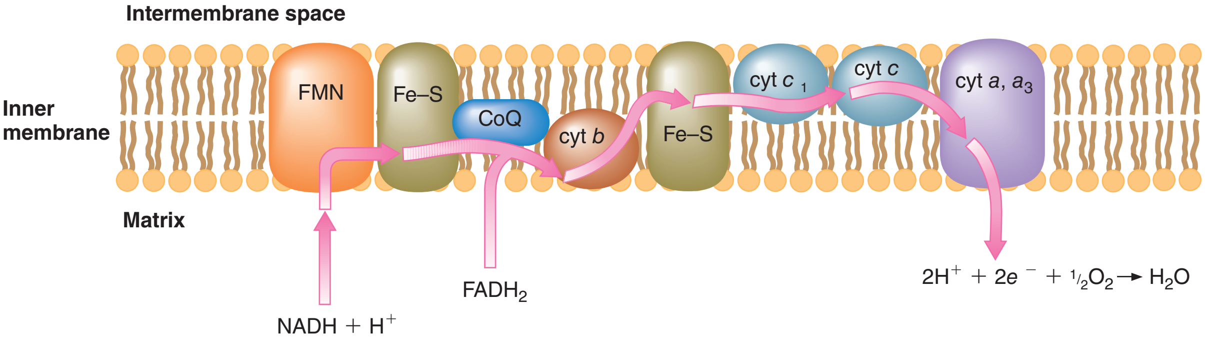


FIGURE 23.10 The electron transport chain. The heavy arrows show the path of the electrons as they pass from one carrier to the next.

Q (CoQ). CoQ is also the entry point into the electron transport chain for the two electrons and two H^+ ions from $FADH_2$. As NADH and $FADH_2$ release their hydrogen atoms and electrons, NAD^+ and FAD are regenerated for reuse in the citric acid cycle.

Four of the five remaining electron carriers are **cytochromes** (abbreviated cyt), which are structurally related proteins that contain an iron group. CoQ passes along the two electrons to two molecules of cytochrome *b*, and the two H^+ ions are given up to the mitochondrion. The electrons are passed along the chain, and in the final step, an oxygen atom accepts the electrons and combines with two H^+ ions to form water.

cytochrome An iron-containing enzyme located in the electron transport chain.

23.7 Oxidative Phosphorylation

Learning Objective 9 List the major features of the chemiosmotic hypothesis.

As electrons are transported along the electron transport chain, a significant amount of free energy is released (52.6 kcal/mol). Some of this energy is conserved by the synthesis of ATP from ADP and P_i. Because this synthesis of ATP (a phosphorylation reaction) is linked to the oxidation of NADH and $FADH_2$, it is termed **oxidative phosphorylation**. It takes place at three different locations of the electron transport chain (see **Figure 23.11**).

oxidative phosphorylation A process coupled with the electron transport chain whereby ADP is converted to ATP.

For each mole of NADH oxidized in the electron transport chain, 2.5 mol of ATP is formed. The free energy required for the phosphorylation of ADP is 7.3 kcal/mol, or 18 kcal for 2.5 mol of ATP. Because the oxidation of NADH liberates 52.6 kcal/mol, coupling the oxidation and phosphorylation reactions conserves 18 kcal/52.6 kcal, or approximately 34% of the energy released.

The electron donor $FADH_2$ enters the electron transport chain later than does NADH. Thus, for every $FADH_2$ oxidized to FAD, only 1.5 ATP molecules are formed during oxidative phosphorylation, and approximately 25% of the released free energy is conserved as ATP.

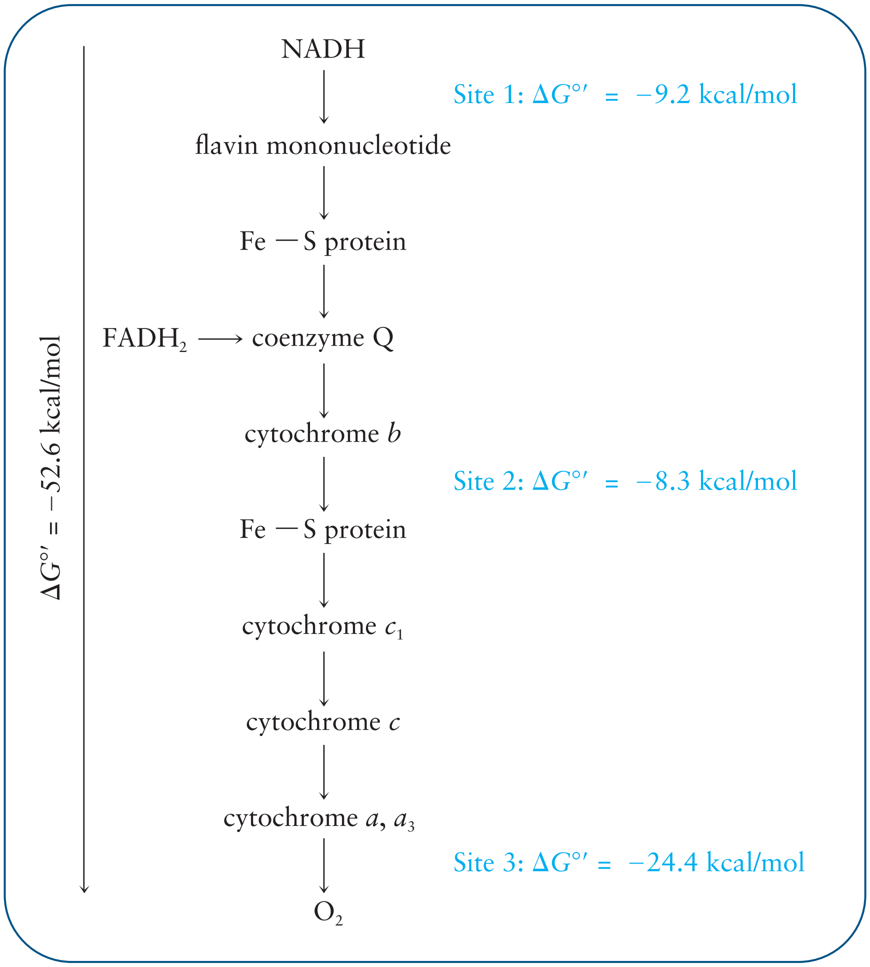
Now we can calculate the energy yield for the entire catabolic pathway (citric acid cycle, electron transport chain, and oxidative phosphorylation combined). According to **Section 23.5**, every acetyl CoA entering the citric acid cycle produces three NADH and one $FADH_2$ plus one GTP, which is equivalent in energy to one ATP. Thus, 10 ATP molecules are formed per molecule of acetyl CoA catabolized.

3 NADH ultimately produce	7.5 ATP
1 $FADH_2$ ultimately produces	1.5 ATP
1 GTP is equivalent to	1.0 ATP
	10.0 ATP total produced

The complex mechanism by which the cell couples the oxidations of the electron transport chain and the synthesis of ATP is believed to involve a flow of protons. This explanation, called the **chemiosmotic hypothesis**, proposes that the flow of electrons through the electron transport chain causes protons to be "pumped" from the matrix across the

chemiosmotic hypothesis The postulate that a proton flow across the inner mitochondrial membrane during operation of the electron transport chain provides energy for ATP synthesis.

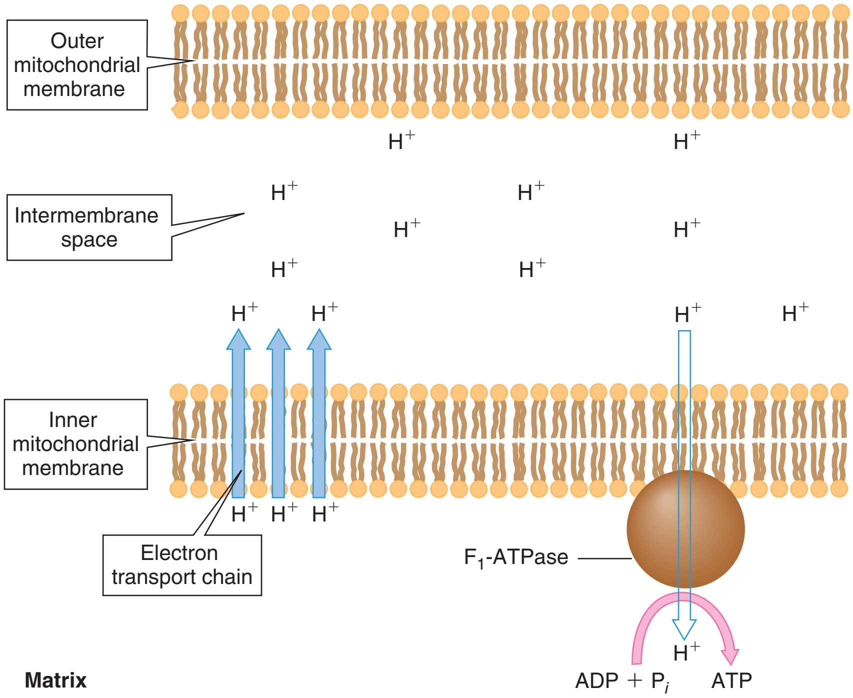
FIGURE 23.11 ATP is synthesized at three sites within the electron transport chain. Energy decreases at other locations result in the release of heat energy.



NADH
flavin mononucleotide
Fe — S protein
$FADH_2$ ⟶ coenzyme Q
cytochrome *b*
Fe — S protein
cytochrome c_1
cytochrome *c*
cytochrome *a*, a_3
O_2
Site 1: $\Delta G^{\circ\prime} = -9.2$ kcal/mol
Site 2: $\Delta G^{\circ\prime} = -8.3$ kcal/mol
Site 3: $\Delta G^{\circ\prime} = -24.4$ kcal/mol
$\Delta G^{\circ\prime} = -52.6$ kcal/mol

inner membrane and into the space between the inner and outer mitochondrial membranes (see **Figure 23.12**). This creates a difference in proton concentration across the inner mitochondrial membrane, along with an electrical potential difference. As a result of the

FIGURE 23.12 The chemiosmotic hypothesis. Electron transport pumps protons (H^+) out of the matrix. The formation of ATP accompanies the flow of protons through F_1-ATPase back into the matrix.



Outer mitochondrial membrane
Intermembrane space
Inner mitochondrial membrane
Electron transport chain
F_1-ATPase
H^+
ADP + P_i
ATP
Matrix

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

concentration and potential differences, protons flow back through the membrane using a channel formed by the enzyme F_1-ATPase. The flow of protons through this enzyme is believed to drive the phosphorylation reaction.

$$\text{ADP} + \text{P}_i \xrightarrow[\quad]{\substack{\text{H}^+ \text{ flow through} \\ \text{F}_1\text{-ATPase}}} \text{ATP} \tag{23.15}$$

Example 23.4 Calculating ATP Production

How many molecules of ATP are produced from one molecule of each of the following:

a. $FADH_2$
b. NADH
c. Acetyl CoA

Solution

a. 1.5
b. 2.5
c. 10.0

✔ **LEARNING CHECK 23.4** How many molecules of ATP are produced from the complete catabolism of the following?

a. Two molecules of $FADH_2$
b. Two molecules of NADH
c. Two molecules of acetyl CoA

23.8 The Complete Oxidation of Glucose

Learning Objective 10 Calculate the amount of ATP produced by the complete oxidation of a mole of glucose.

The information given to this point about glycolysis, the citric acid cycle, and the electron transport chain almost makes it possible to calculate the ATP yield from the total oxidation of 1 mol of glucose. However, one more factor must be considered. NADH produced in the cytoplasm during glycolysis does not pass through the mitochondrial membrane to the site of the electron transport chain. Brain and muscle cells employ a transport mechanism that passes electrons from the cytoplasmic NADH through the membrane to FAD molecules inside the mitochondria, forming $FADH_2$. In **Section 23.7**, we pointed out that one molecule of $FADH_2$ gives 1.5 molecules of ATP using the electron transport chain. Thus, with this transport mechanism, one molecule of cytoplasmic NADH generates only 1.5 molecules of ATP, whereas 2.5 molecules of ATP come from each molecule of mitochondrial NADH. A more efficient shuttle mechanism is found in liver, heart, and kidney cells, where one cytoplasmic NADH results in one mitochondrial NADH. Thus, 2.5 molecules of ATP are formed in this case.

This production of ATP from the complete aerobic catabolism of 1 mol of glucose in the liver is summarized in **Table 23.1**. Notice from the table that of the 32 mol of ATP generated, the great majority (28 mol) is formed as a result of oxidative phosphorylation (last category in **Table 23.1**). In **Section 23.4**, we learned that only 2 mol of ATP is produced per mole of glucose by lactate fermentation and by alcoholic fermentation. Thus, in terms of ATP production from fuels, the complete aerobic oxidation of glucose is 16 times more efficient than either lactate or alcoholic fermentation.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

TABLE 23.1 The ATP Yield from the Complete Oxidation of 1 mol of Glucose

Reaction	Comments	Yield of ATP (moles)
Cytoplasmic reactions		
Glycolysis		
glucose → glucose-6-phosphate	1 mol consumes 1 ATP	−1
glucose-6-phosphate → fructose-1,6-bisphosphate	1 mol consumes 1 ATP	−1
glyceraldehyde-3-phosphate → 1,3-bisphosphoglycerate	2 mol produces 2 mol of cytoplasmic NADH	
1,3-bisphosphoglycerate → 3-phosphoglycerate	2 mol produces 2 ATP	+2
phosphoenolpyruvate → pyruvate	2 mol produces 2 ATP	+2
Mitochondrial reactions		
Oxidation of pyruvate		
pyruvate → acetyl CoA + CO_2	2 mol produces 2 NADH	
Citric acid cycle		
isocitrate → α-ketoglutarate + CO_2	2 mol produces 2 NADH	
α-ketoglutarate → succinyl CoA + CO_2	2 mol produces 2 NADH	
succinyl CoA → succinate	2 mol produces 2 GTP	+2
succinate → fumarate	2 mol produces 2 $FADH_2$	
malate → oxaloacetate	2 mol produces 2 NADH	
Electron transport chain and oxidative phosphorylation		
2 cytoplasmic NADH formed in glycolysis	each yields 2.5 ATP	+5[a]
2 NADH formed in the oxidation of pyruvate	each yields 2.5 ATP	+5
2 $FADH_2$ formed in the citric acid cycle	each yields 1.5 ATP	+3
6 NADH formed in the citric acid cycle	each yields 2.5 ATP	+15
	Net yield of ATP	+32

[a] In muscle and brain cells, 3 ATP are produced in this step and only 30 ATP overall.

Another useful way to look at the efficiency of the complete oxidation of glucose is to compare the amount of free energy available in glucose and the amount of free energy stored in synthesized ATP.

Glucose oxidation:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O \qquad \Delta G^{\circ\prime} = -686 \text{ kcal/mol} \tag{23.16}$$

ATP synthesis:

$$32ADP + 32P_i \rightarrow 32ATP + 32H_2O \qquad \Delta G^{\circ\prime} = +234 \text{ kcal/mol} \tag{23.17}$$

Overall reaction:

$$C_6H_{12}O_6 + 6O_2 + 32ADP + 32P_i \rightarrow 6CO_2 + 32ATP + 38H_2O \tag{23.18}$$

$$\text{Total: } \Delta G^{\circ\prime} = -452 \text{ kcal/mol}$$

Thus, glucose oxidation liberates 686 kcal/mol, whereas the synthesis of 32 mol of ATP stores 234 kcal/mol. The efficiency of energy stored is

$$\frac{\text{energy stored}}{\text{energy available}} \times 100 = \frac{234 \text{ kcal/mol}}{686 \text{ kcal/mol}} \times 100 = 34.1\%$$

It is remarkable that living cells can capture 34% of the released free energy and make it available to do biochemical work. By contrast, an automobile engine makes available only about 20%–30% of the energy actually released by burning gasoline.

Example 23.5 Calculating ATP Production from Glucose

List the amount of ATP produced by the complete oxidation of a mole of glucose in the following locations:

a. liver cells
b. muscle cells
c. brain cells

Solution

a. 32 moles
b. 30 moles
c. 30 moles

✔ **LEARNING CHECK 23.5** For the complete oxidation of one mole of glucose, indicate how many moles of ATP (or GTP) are produced in the following:

a. Glycolysis
b. Citric acid cycle
c. Electron transport chain

23.9 Glycogen Metabolism

Learning Objective 11 Explain the importance of the processes of glycogenesis and glycogenolysis.

23.9A Glycogen Synthesis

Glucose consumed in excess of immediate body requirements is converted to glycogen (see **Section 17.8**), which is stored primarily in the liver and muscle tissue. The liver of an average adult can store about 110 g of glycogen, and the muscles can store about 245 g. The process by which glucose is converted to glycogen is called **glycogenesis**. Glycogenesis can occur in all cells, but it is an especially important function of liver and muscle cells. The net result of this anabolic process is the bonding of glucose units to a growing glycogen chain, with the hydrolysis of a high-energy nucleotide, UTP (uridine triphosphate) (see **Section 22.7**), providing the energy. The enzyme glycogen synthase forms the new α(1 → 4) linkages between each glucose unit and lengthens the chain. The α(1 → 6) branch points on the chain are inserted by a branching enzyme called amylo (1,4-1,6)-trans-glycosylase.

glycogenesis The synthesis of glycogen from glucose.

The overall process of glycogenesis is summarized by Reaction 23.19:

$$(\text{glucose})_n \xrightarrow[\text{UTP} \quad \text{UDP} + \text{P}_i]{} (\text{glucose})_{n+1} = \text{glycogen} \tag{23.19}$$

23.9B Glycogen Breakdown

The breakdown of glycogen back to glucose is called **glycogenolysis**. Although major amounts of glycogen are stored in both muscle tissue and the liver, glycogenolysis can occur in the liver (and kidney and intestinal cells) but not in muscle tissue because one essential enzyme (glucose-6-phosphatase) is lacking. The first step in glycogen breakdown is the cleavage of α(1 → 4) linkages, catalyzed by glycogen phosphorylase. In this reaction, glucose units are released from the glycogen chain as glucose-1-phosphate:

glycogenolysis The breakdown of glycogen to glucose.

$$\underset{\text{glycogen}}{(\text{glucose})_n} + \text{P}_i \rightarrow \underset{\substack{\text{glycogen with one}\\ \text{fewer glucose unit}}}{(\text{glucose})_{n-1}} + \text{glucose-1-phosphate} \tag{23.20}$$

STUDY TOOLS 23.1

Key Numbers for ATP Calculations

It is important to be able to determine the energy yield in terms of the number of ATP molecules produced by the stepwise catabolism of glucose. Some of the relationships used in this determination will be used in the next chapter to calculate the energy yield from fatty acid catabolism. The three key substances to focus on are acetyl CoA, NADH, and $FADH_2$. Every mitochondrial NADH produces 2.5 ATP molecules, and every $FADH_2$ produces 1.5 ATP molecules. Every acetyl CoA that passes through the citric acid cycle gives 3 NADH, 1 $FADH_2$, and 1 GTP, which in turn produce a total of 10 ATP molecules. These reactions are outlined here.

Catabolic step		Energy production
Glycolysis (1 glucose ⟶ 2 pyruvate)	produces	2 NADH (cytoplasmic) + 2 ATP
		liver, heart, kidneys → 5 ATP
		brain, muscle → (3 ATP)
Oxidation of 2 pyruvates to 2 acetyl CoA	produces	2 NADH (mitochondrial) → 5 ATP
Citric acid cycle, one turn	produces	3 NADH → 7.5 ATP
		1 $FADH_2$ → 1.5 ATP
		1 GTP → 1.0 ATP
		10.0 ATP
Citric acid cycle, two turns	produce	2 × 10 = 20 ATP
		Total/glucose molecule = 32 ATP (30 ATP)

The second step in glycogen breakdown is the cleavage of the $\alpha(1 \rightarrow 6)$ linkages by hydrolysis, which is carried out by the debranching enzyme. When the branch points are eliminated, the phosphorylase can then continue to act on the rest of the chain.

In the debranching reaction, phosphoglucomutase catalyzes the isomerization of glucose-1-phosphate to glucose-6-phosphate:

$$\text{glucose-1-phosphate} \rightleftarrows \text{glucose-6-phosphate} \tag{23.21}$$

The final step in glycogen breakdown is the hydrolysis of glucose-6-phosphate to produce free glucose. The enzyme for this reaction, glucose-6-phosphatase, is the one found only in liver, kidney, and intestinal cells:

$$\text{glucose-6-phosphate} + H_2O \rightarrow \text{glucose} + P_i \tag{23.22}$$

Without glucose-6-phosphatase, muscle cells cannot form free glucose from glycogen. However, they can carry out the first two steps of glycogenolysis to produce glucose-6-phosphate. This form of glucose is the first intermediate in the glycolysis pathway and can still be used to produce energy even if the reaction does not proceed to the formation of D-glucose. In this way, muscle cells utilize glycogen only for energy production. An important function of the liver is to maintain a relatively constant level of blood glucose, necessitating that this organ have a broader biochemical function than muscle. Thus, it has the capacity to degrade glycogen all the way to glucose, which is released into the blood during muscular activity and between meals.

✔ **LEARNING CHECK 23.6** What enzyme enables the liver to form glucose from glycogen? Why can't muscles carry out the same conversion?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

23.10 Gluconeogenesis

Learning Objective 12 Describe gluconeogenesis and the operation of the Cori cycle.

The supply of glucose in the form of liver and muscle glycogen can be depleted by about 12–18 hours of fasting. These stores of glucose are also depleted in a short time as a result of heavy work or strenuous exercise (see **Figure 23.13**). Nerve tissue, including the brain, would be deprived of glucose under such conditions if the only source was glycogen. Fortunately, a metabolic pathway exists that overcomes this problem.

iStock.com/TarpMagnus

FIGURE 23.13 Gluconeogenesis provides a source of glucose when glycogen supplies are exhausted after vigorous exercise.

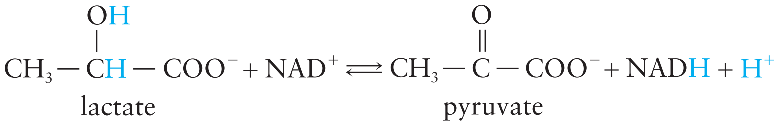
Glucose can be synthesized from noncarbohydrate materials in a process called **gluconeogenesis**. When carbohydrate intake is low and when glycogen stores are depleted, the carbon skeletons of lactate, glycerol (derived from the hydrolysis of fats), and certain amino acids are used to synthesize pyruvate, which is then converted to glucose:

$$\text{(lactate, certain amino acids, glycerol)} \rightarrow \text{pyruvate} \rightarrow \text{glucose} \qquad (23.23)$$

About 90% of gluconeogenesis takes place in the liver. Very little occurs in the kidneys, brain, skeletal muscle, or heart, even though these organs have a high demand for glucose. Thus, gluconeogenesis taking place in the liver helps maintain the blood glucose level so that tissues needing glucose can extract it from the blood.

Gluconeogenesis involving lactate is especially important. As might be expected, this process follows a separate and different pathway from glycolysis. During active exercise, lactate levels increase in muscle tissue, and the compound diffuses out of the tissue into the blood. It is transported to the liver, where lactate dehydrogenase, the enzyme that catalyzes lactate formation in muscle, converts it back to pyruvate:

gluconeogenesis The synthesis of glucose from noncarbohydrate molecules.



$$\underset{\text{lactate}}{CH_3-\overset{\overset{\displaystyle OH}{|}}{C}H-COO^-} + NAD^+ \rightleftharpoons \underset{\text{pyruvate}}{CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-COO^-} + NADH + H^+ \qquad (23.24)$$

The pyruvate is then converted to glucose by the gluconeogenesis pathway, and the glucose enters the blood. In this way, the liver increases a low blood glucose level and makes glucose available to muscle. This cyclic process, involving the transport of lactate from muscle to the liver, the resynthesis of glucose by gluconeogenesis, and the return of glucose to muscle tissue, is called the **Cori cycle** (see **Figures 23.14** and **23.15**).

Cori cycle The process in which glucose is converted to lactate in muscle tissue, lactate is reconverted to glucose in the liver, and glucose is returned to the muscle.

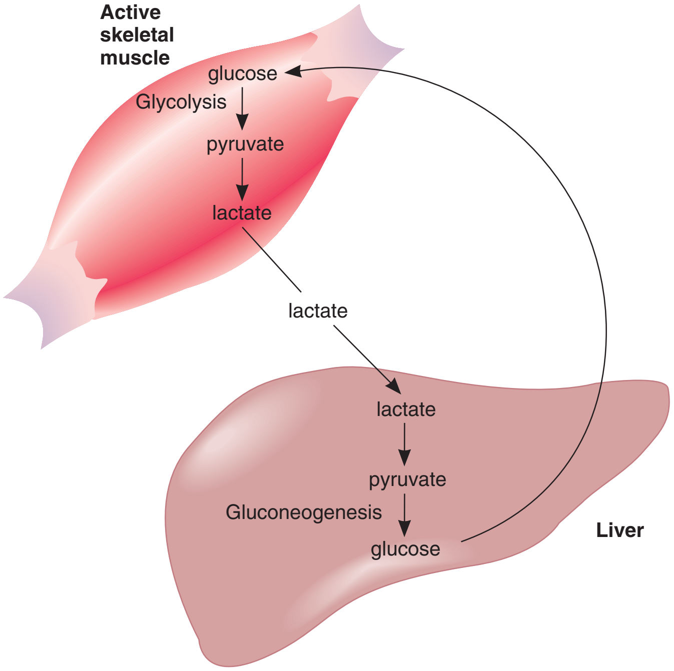


FIGURE 23.14 The Cori cycle, showing the relationship between glycolysis (in the muscle) and gluconeogenesis (in the liver).

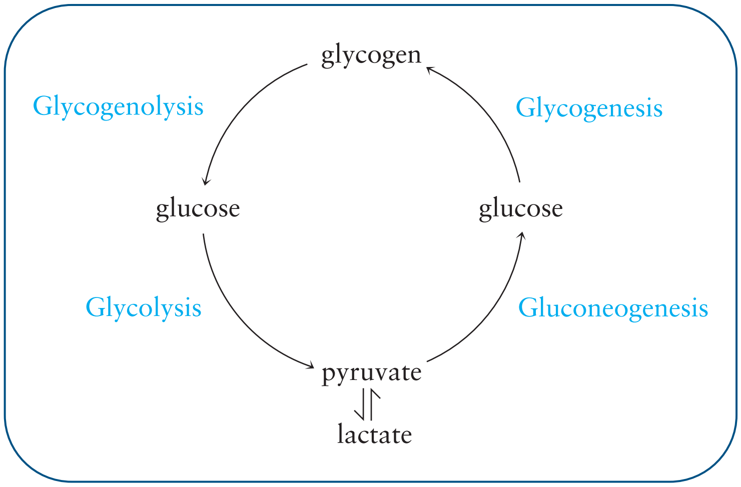
Everett Collection Historical/Alamy Stock Photo

FIGURE 23.15 Gerty and Carl Cori were co-winners of the Nobel Prize in 1947 for their discovery of the reactions in gluconeogenesis.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Figure 23.16 Shows the relationship of gluconeogenesis to the other major pathways of glucose metabolism.

FIGURE 23.16 A summary of the major pathways in glucose metabolism. Note that the breakdown processes end in *-lysis*, whereas the synthesis pathways end in *-genesis*.



23.11 The Hormonal Control of Carbohydrate Metabolism

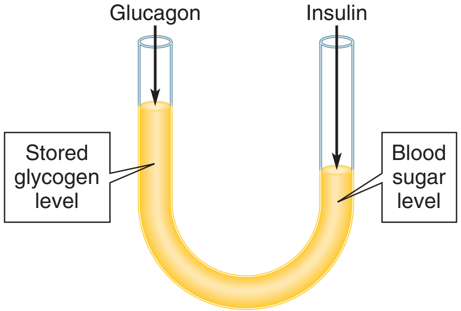
Learning Objective 13 Describe how hormones regulate carbohydrate metabolism.

It is important that metabolic pathways be responsive to cellular conditions so that energy is not wasted in producing unneeded materials. Besides the regulation of enzymes at key control points (see **Section 23.3**), the body also uses three important regulatory hormones: epinephrine, glucagon, and insulin.

In **Section 23.2**, we pointed out that when carbohydrates are consumed, the blood glucose level increases. This increase signals the β-cells of the pancreas to release a small amount of the hormone insulin into the bloodstream. The hormone enhances the absorption of glucose from the blood into cells of active tissue such as skeletal and heart muscles (see **Section 19.6**). In addition, insulin increases the rate of synthesis of glycogen, fatty acids, and proteins and stimulates glycolysis. Each of these activities uses up glucose. As a result of insulin released into the bloodstream, the blood glucose level begins to decrease within 1 hour after carbohydrates have been ingested and returns to normal within about 3 hours.

Glucagon, a second polypeptide hormone, is synthesized and secreted by the α-cells of the pancreas. Glucagon activates the breakdown of glycogen (glycogenolysis) in the liver and thus counteracts the effect of insulin by raising blood glucose levels. **Figure 23.17** emphasizes the fact that insulin and glucagon work in opposition to each other and that the blood sugar level at any given time depends, in part, on the biochemical balance between these two hormones. Blood levels of glucose are also influenced to some degree by growth hormones and adrenal cortex steroids.

FIGURE 23.17 The biochemical balance between two opposing hormones, insulin and glucagon.



The third hormone affecting glucose metabolism is epinephrine, synthesized by the adrenal gland (see **Section 16.6**). Epinephrine stimulates glycogen breakdown in muscles and, to a smaller extent, in the liver. This glycogenolysis reaction—usually a response to pain, anger, or fear—provides energy for a sudden burst of muscular activity. **Table 23.2** summarizes the hormonal control of glycogen.

TABLE 23.2 The Hormonal Control of Glycogen

Hormone	Source	Effect on Glycogen	Impact on Blood Glucose
Insulin	β-cells of pancreas	Increases formation	Lowers blood glucose levels
Glucagon	α-cells of pancreas	Activates breakdown of liver glycogen	Raises blood glucose levels
Epinephrine	Adrenal medulla	Stimulates breakdown	Raises blood glucose levels

Health Career Description

SONOGRAPHER

According to the American Registry for Diagnostic Medical Sonography (ARDMS), "Sonography is a painless non-invasive procedure that uses high-frequency sound waves to produce visual images of organs, tissues, or blood flow inside the body."

Sonography encompasses several specialties, including abdominal sonographer, breast sonographer, neurosonographer, gynecological sonographer, echocardiographer, vascular sonographer, and musculoskeletal sonographer. Each of these specialties requires separate certifications found under ARDMS sonography assessments.

Sonographers use a transducer to introduce sound waves into the body that may then be converted to visual imagery. Sonographers create videos of the examinations performed and write reports interpreting the results for physicians.

Students may become sonographers by pursuing a 2-year program at a technical college or a 4-year bachelor degree. They may also pursue a 1-year certificate if they are already trained in a health profession. Weber State University in Ogden, Utah, offers a multispecialty bachelor's degree called Diagnostic Medical Sonography (DMS). This bachelors-degree program builds on an Associate of Radiologic Sciences degree. At the end of the 4-year degree program, students are ready to test in cardiac, medical, and vascular sonography as well as a variety of subspecialties.

Because sonographers work with patients in very intimate settings, excellent communication skills and strict adherence to privacy standards are essential. Sonographers must be able to treat patients with respect and kindness, while also completing the job of obtaining the images ordered by the physician.

Sonographers may work in a variety of settings depending on specialty. A wide range of possibilities exist for sonographers, from high-demand jobs in hospitals, to more predictable regular shift work in clinics. The need for sonographers is expected to increase in the future, making it an excellent career choice.

Sources: American Registry for Diagnostic Medical Sonographers (ARDMS). (n.d.). How to Become a Sonographer. Retrieved May 17, 2020 from https://www.ardms.org/how-to-become-a-sonographer/; Weber State University. (n.d.). Diagnostic Medical Sonography. Retrieved May 17, from 2020 from https://www.weber.edu/RadSci/diagnosticemphases.html

Concept Summary

23.1 The Digestion of Carbohydrates

Learning Objective: Can you identify the products of carbohydrate digestion?

- Glucose is the key food molecule for most organisms.
- It is the central substance in carbohydrate metabolism.
- During digestion, carbohydrates are hydrolyzed to the monosaccharides glucose, fructose, and galactose.
- These are absorbed into the bloodstream through the lining of the small intestine.

23.2 Blood Glucose

Learning Objective: Can you explain the importance to the body of maintaining proper blood sugar levels?

- Glucose is the most abundant carbohydrate in the blood.
- The liver regulates blood glucose levels so that a sufficient concentration is always available to meet the body's energy needs.
- A lower-than-normal blood glucose level is referred to as hypoglycemia.
- A higher-than-normal blood glucose level is termed hyperglycemia.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

23.3 Glycolysis

Learning Objective: Can you list the starting material and products of the glycolysis pathway? Can you describe how the glycolysis pathway is regulated in response to cellular needs?

- Glycolysis is a series of 10 reactions that occur in the cytoplasm of cells.
- It is a process in which one glucose molecule is converted into two molecules of pyruvate.
- Two molecules of ATP and two molecules of NADH are produced in the process.
- Both galactose and fructose are converted into intermediates that enter the glycolysis pathway.
- The glycolysis pathway is controlled by the regulation of three key enzymes in the reaction sequence.

23.4 The Fates of Pyruvate

Learning Objective: Can you name the three fates of pyruvate?

- Pyruvate, the product of glycolysis, has three different fates.
- Under aerobic conditions, pyruvate enters mitochondria and is converted to acetyl CoA.
- The acetyl CoA enters the citric acid cycle.
- Products of the citric acid cycle enter the electron transport chain, where oxidation is completed and ATP is synthesized.
- A second fate of pyruvate is conversion to lactate.
- This takes place in anaerobic microorganisms and in humans when glycolysis occurs faster than the oxygen-dependent citric acid cycle and the electron transport chain can operate.
- Some microorganisms convert pyruvate to ethanol, the third fate of pyruvate.
- In each of these three processes, NAD^+ is regenerated so that glycolysis can continue.

23.5 The Citric Acid Cycle

Learning Objective: Can you identify the two major functions of the citric acid cycle? Can you describe how the citric acid cycle is regulated in response to cellular energy needs?

- The citric acid cycle generates NADH and $FADH_2$, which are necessary for ATP synthesis.
- It also produces intermediates used for biosynthesis.
- This pathway consists of eight reactions that process incoming molecules of acetyl CoA.
- The carbon atoms leave the cycle in the form of molecules of CO_2.
- The hydrogen atoms and electrons leave the cycle in the form of reduced coenzymes NADH and $FADH_2$.
- The cycle is regulated by three allosteric enzymes in response to cellular levels of ATP.
- One acetyl CoA molecule entering the citric acid cycle produces three molecules of NADH, one of $FADH_2$, and one of GTP.

23.6 The Electron Transport Chain

Learning Objective: Can you explain the function of the electron transport chain and describe how electrons move down the chain?

- This pathway involves a series of reactions that pass electrons from NADH and $FADH_2$ to molecular oxygen.
- Each carrier in the series has an increasing affinity for electrons.
- Four of the carriers, which are referred to as cytochromes, contain iron, which accepts and then transfers the electrons.
- As NADH and $FADH_2$ release their hydrogen atoms and electrons, NAD^+ and FAD are regenerated for return to the citric acid cycle.

23.7 Oxidative Phosphorylation

Learning Objective: Can you list the major features of the chemiosmotic hypothesis?

- At three sites within the electron transport chain, the decrease in free energy is sufficient to convert ADP to ATP.
- One molecule of NADH produces 2.5 molecules of ATP.
- $FADH_2$, which enters the chain one step later, produces 1.5 molecules of ATP.
- According to the chemiosmotic hypothesis, the synthesis of ATP takes place because of a flow of protons across the inner mitochondrial membrane.

23.8 The Complete Oxidation of Glucose

Learning Objective: Can you calculate the amount of ATP produced by the complete oxidation of a mole of glucose?

- The complete oxidation of 1 mol of glucose produces 32 (or 30) mol of ATP.
- In contrast, lactate and alcoholic fermentation produce only 2 mol of ATP.

23.9 Glycogen Metabolism

Learning Objective: Can you explain the importance of the processes of glycogenesis and glycogenolysis?

- When blood glucose levels are high, excess glucose is converted into glycogen by the process of glycogenesis.
- The glycogen is stored within the liver and muscle tissue.
- Glycogenolysis is the breakdown of glycogen into glucose.
- It occurs when muscles need energy and when the liver is restoring a low blood sugar level to normal.

23.10 Gluconeogenesis

Learning Objective: Can you describe gluconeogenesis and the operation of the Cori cycle?

- Lactate, certain amino acids, and glycerol can be converted into glucose.
- This process, called gluconeogenesis, takes place in the liver when glycogen supplies are being depleted and when carbohydrate intake is low.
- Gluconeogenesis from lactate is especially important during periods of high muscle activity.
- The liver converts excess lactate from the muscles into glucose, which is then cycled back to the muscles.
- This process is called the Cori cycle.

23.11 The Hormonal Control of Carbohydrate Metabolism

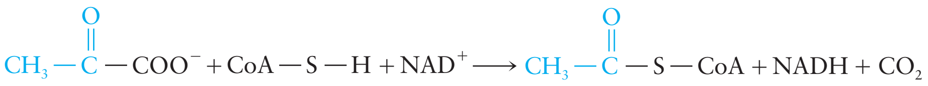
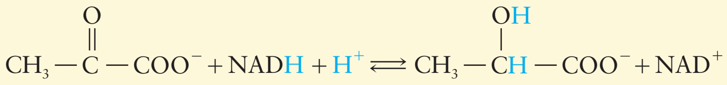
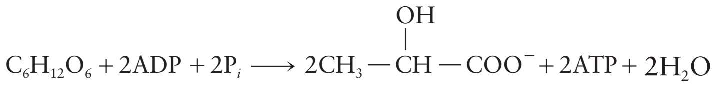
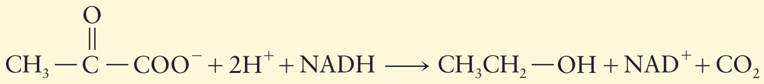
Learning Objective: Can you describe how hormones regulate carbohydrate metabolism?

- Three hormones exert major interactive effects on carbohydrate metabolism: insulin, glucagon, and epinephrine.
- Insulin promotes the uptake and utilization of glucose by the cells.
- Thus, insulin lowers blood sugar levels.
- Glucagon stimulates the conversion of glycogen to glucose and thus raises blood glucose levels.
- Epinephrine is released in response to anger, fear, and excitement.
- It also stimulates the release of glucose from glycogen and raises blood glucose levels.

Key Terms and Concepts

Aerobic (23.4)
Alcoholic fermentation (23.4)
Anaerobic (23.4)
Blood sugar level (23.2)
Chemiosmotic hypothesis (23.7)
Citric acid cycle (23.5)
Cori cycle (23.10)
Cytochrome (23.6)
Electron transport chain (23.6)
Gluconeogenesis (23.10)
Glucosuria (23.2)
Glycogenesis (23.9)
Glycogenolysis (23.9)
Glycolysis (23.3)
Hyperglycemia (23.2)
Hypoglycemia (23.2)
Lactate fermentation (23.4)
Oxidative phosphorylation (23.7)
Renal threshold (23.2)

Key Equations

1. Glycolysis (**Section 23.3**): $\text{glucose} + 2P_i + 2ADP + 2NAD^+ \longrightarrow 2\ \text{pyruvate} + 2ATP + 2NADH + 4H^+ + 2H_2O$		Reaction 23.5
2. Oxidation of pyruvate to acetyl CoA (**Section 23.4**):  $CH_3-\overset{\overset{O}{\|}}{C}-COO^- + CoA-S-H + NAD^+ \longrightarrow CH_3-\overset{\overset{O}{\|}}{C}-S-CoA + NADH + CO_2$		Reaction 23.7
3. Reduction of pyruvate to lactate (**Section 23.4**):	 $CH_3-\overset{\overset{O}{\|}}{C}-COO^- + NADH + H^+ \rightleftharpoons CH_3-\overset{\overset{OH}{\vert}}{CH}-COO^- + NAD^+$	Reaction 23.8
4. Net reaction of lactate fermentation (**Section 23.4**):	 $C_6H_{12}O_6 + 2ADP + 2P_i \longrightarrow 2CH_3-\overset{\overset{OH}{\vert}}{CH}-COO^- + 2ATP + 2H_2O$	Reaction 23.9
5. Reduction of pyruvate to ethanol (**Section 23.4**):	 $CH_3-\overset{\overset{O}{\|}}{C}-COO^- + 2H^+ + NADH \longrightarrow CH_3CH_2-OH + NAD^+ + CO_2$	Reactions 23.10 and 23.11
6. Net reaction of alcoholic fermentation (**Section 23.4**):	$C_6H_{12}O_6 + 2ADP + 2P_i \longrightarrow 2CH_3CH_2-OH + 2CO_2 + 2ATP$	Reaction 23.12
7. The citric acid cycle (**Section 23.5**): $\text{acetyl CoA} + 3NAD^+ + FAD + GDP + P_i + 2H_2O \longrightarrow 2CO_2 + CoA-S-H + 3NADH + 2H^+ + FADH_2 + GTP$		Reaction 23.13
8. The electron transport chain (**Section 23.6**):	$4H^+ + 4e^- + O_2 \longrightarrow 2H_2O$	Reaction 23.14

9. Oxidative phosphorylation (**Section 23.7**):	ADP + $P_i \longrightarrow$ ATP	Reaction 23.15
10. Complete oxidation of glucose (**Section 23.8**):	$C_6H_{12}O_6 + 6O_2 + 32ADP + 32P_i \longrightarrow 6CO_2 + 32ATP + 38H_2O$	Reaction 23.18
11. Glycogenesis (**Section 23.9**):	glucose $\longrightarrow$ glycogen	Reaction 23.19
12. Glycogenolysis (**Section 23.9**):	glycogen $\longrightarrow$ glucose	Reactions 23.20, 23.21, and 23.22
13. Gluconeogenesis (**Section 23.10**):	$\left\{\begin{array}{c}\text{lactate,}\\ \text{certain amino acids,}\\ \text{glycerol}\end{array}\right\} \longrightarrow \text{pyruvate} \longrightarrow \text{glucose}$	Reaction 23.23

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

The Digestion of Carbohydrates (Section 23.1)

23.1 Why is glucose considered the pivotal compound in carbohydrate metabolism?

23.2* Name the products produced by the digestion of

a. starch
b. lactose
c. sucrose
d. maltose

23.3 List the three major monosaccharides produced by the digestion of carbohydrates.

23.4 Describe the fate of fructose and galactose after digestion is completed.

23.5 What type of reaction is involved as carbohydrates undergo digestion?

Blood Glucose (Section 23.2)

23.6 Describe what is meant by the terms *blood sugar level* and *normal fasting level.*

23.7 What range of concentrations for glucose in blood is considered a normal fasting level?

23.8 How do each of the following terms relate to blood sugar level?

a. Hypoglycemia
b. Hyperglycemia
c. Renal threshold
d. Glucosuria

23.9 Convert a normal blood sugar level of 100.0 mg/100.0 mL into molarity. One mol of glucose is 180.2 g.

23.10 Insulin is a hormone that acts like a key, opening doors on cell membranes that allows glucose to enter the cell so it can be metabolized. Would insulin be used to treat hyperglycemia or hypoglycemia? Explain your answer.

23.11 Early in the history of medicine, doctors would taste the urine of patients looking for "sweetness." What blood sugar level–related condition were they testing for?

23.12 Explain how the synthesis and degradation of glycogen in the liver help regulate blood sugar levels.

23.13 Explain why severe hypoglycemia can be very serious.

Glycolysis (Section 23.3)

23.14 What is the main purpose of glycolysis?

23.15 What is the starting material for glycolysis? The product?

23.16 In what part of the cell does glycolysis take place?

23.17 How many steps in glycolysis require ATP? How many steps produce ATP? What is the net production of ATP from one glucose molecule undergoing glycolysis?

23.18 Which coenzyme serves as an oxidizing agent in glycolysis?

23.19 What is the third control point in glycolysis? How is it responsive to cellular needs?

23.20 How many steps in glycolysis require NADH? How many steps produce NADH? What is the net production of NADH from one glucose molecule undergoing glycolysis?

23.21 Explain what is meant by feedback inhibition.

23.22 Explain what is meant by allosteric regulation.

23.23 Using **Figures 23.3** and **23.4**, complete the following word equations by replacing the question mark with the name of the substance or enzyme needed.

a. $\text{Glucose} + \text{ATP} \xrightarrow{?} \text{glucose-6-phosphate} + \text{ADP} + H^+$

b. $? \xrightarrow{\text{enzyme}} \text{phosphoenolpyruvate} + \text{water}$

c. $\text{3-phosphoglycerate} \xrightarrow{\text{enzyme}} ?$

d. $\text{1,3-bisphosphoglycerate} + ? \xrightarrow{\text{enzyme}} \text{3-phosphoglycerate} + \text{ATP}$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

23.24 Using **Figures 23.3** and **23.4**, complete the following word equations by replacing the question mark with the name of the substance or enzyme needed.

a. Glucose-6-phosphate $\xrightarrow{\text{enzyme}}$?

b. ? $\xrightarrow{\text{enzyme}}$ dihydroxyacetone phosphate + glyceraldehyde-3-phosphate

c. 3-phosphoenolpyruvate + ADP + H^+ $\xrightarrow{?}$ pyruvate + ATP

d. Fructose-6-phosphate $\xrightarrow{?}$ fructose-1,6-bisphosphate

23.25 Explain how fructose and galactose can enter the glycolysis pathway.

23.26 Explain how a high concentration of glucose-6-phosphate causes a decrease in the rate of glycolysis.

23.27 Why is the conversion of fructose-6-phosphate to fructose-1, 6-bisphosphate sometimes called the "committed step" of glycolysis?

The Fates of Pyruvate (Section 23.4)

23.28 Distinguish between the terms *aerobic* and *anaerobic.*

23.29 What are the three possible fates for pyruvate produced from glycolysis?

23.30 The reduction of pyruvate to lactate produces NAD^+ from NADH. In which step of glycolysis is NAD^+ used?

23.31 Typically, the cellular concentrations of NAD^+ are less than the cellular concentrations of glucose. If the cell has converted all of its NAD^+ to NADH, can glycolysis continue? Explain your answer.

23.32* Explain how lactate formation allows glycolysis to continue under anaerobic conditions.

23.33 Compare the fate of pyruvate in the body under (a) aerobic conditions and (b) anaerobic conditions.

23.34 Write a summary equation for the conversion of glucose to:

a. lactate

b. pyruvate

c. ethanol

23.35 Wine makers use alcoholic fermentation to make wine from grapes. If the starting grapes are sweeter, what will happen to the alcohol content of that wine? Explain your answer.

23.36* What is the fate of the pyruvate molecule's carboxylate group during alcoholic fermentation? Explain how ethanol formation from pyruvate allows yeast to survive with limited oxygen supplies.

The Citric Acid Cycle (Section 23.5)

23.37 What are two other names for the citric acid cycle?

23.38 What is the primary function of the citric acid cycle in ATP production? What other vital role is served by the citric acid cycle?

23.39 Why is it appropriate to refer to the sequence of reactions in the citric acid cycle as a cycle?

23.40 Describe the citric acid cycle by identifying the following:

a. The fuel needed by the cycle

b. The form in which carbon atoms leave the cycle

c. The form in which hydrogen atoms and electrons leave the cycle

23.41* The citric acid cycle is located in close cellular proximity to the electron transport chain. Why?

23.42 How many molecules of each of the following are produced by one run through the citric acid cycle?

a. NADH

b. $FADH_2$

c. GTP

d. CO_2

23.43 Write reactions for the steps in the citric acid cycle that involve oxidation by NAD^+.

23.44 Write a reaction for the step in the citric acid cycle that involves oxidation by FAD.

23.45 Write a reaction for the step in the citric acid cycle that involves the phosphorylation of GDP. What is the structural difference between ATP and GTP? Explain why GTP can function as a high-energy compound.

23.46 Write word reactions for the steps in the citric acid cycle that involve the release of CO_2.

23.47 Although oxygen (O_2) is not used directly in the citric acid cycle, the cycle cannot operate under anaerobic conditions. Explain why.

23.48 The reactions in the citric acid cycle involve enzymes.

a. Identify the enzymes at the three control points.

b. Each control-point enzyme is inhibited by NADH and ATP. Explain how this enables the cell to be responsive to energy needs.

c. Two of the control-point enzymes are activated by ADP. Explain the benefit of this regulation to the cell.

The Electron Transport Chain (Section 23.6)

23.49 What is the primary function of the electron transport chain?

23.50 Identify the cellular location for each of the following:

a. Glycolysis

b. Citric acid cycle

c. Electron transport chain

23.51 Which coenzymes bring electrons to the electron transport chain?

23.52 List the participants of the electron transport chain in the order in which they accept electrons.

23.53 What are the oxidized forms of the coenzymes that leave the electron transport chain after donating their electrons? Where do the oxidized coenzymes return to?

23.54 What is the role of the cytochromes in the electron transport chain?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

23.55 What is the role of oxygen in the functioning of the electron transport chain? Write a reaction that summarizes the fate of the oxygen.

23.56 Iron deficiency can reduce the number of active cytochrome centers in the electron transport chain. Use this information to explain why fatigue is a common symptom of iron deficiency.

Oxidative Phosphorylation (Section 23.7)

23.57 The third stage in the oxidation of foods to provide energy involves oxidative phosphorylation. What is oxidized? What is phosphorylated?

23.58 How many ATP molecules are synthesized when NADH passes electrons to molecular oxygen?

23.59 How many ATP molecules are synthesized when $FADH_2$ passes electrons to molecular oxygen?

23.60 Explain what is meant by the statement: "Oxidation of NADH in the electron transport chain results in 34% energy conservation."

23.61 Explain why NADH and $FADH_2$ molecules do not yield the same number of ATP molecules.

23.62 How many ATP molecules can be formed from one turn of the citric acid cycle, assuming that the products of the cycle enter the electron transport chain.

23.63 How many ATP molecules can be formed by the oxidation of 10 acetyl CoA molecules in the common catabolic pathway?

23.64 Identify the steps in the electron transport chain where ATP is synthesized.

23.65 The change in free energy for the complete oxidation of glucose to CO_2 and H_2O is -686 kcal per mole of glucose. If all this free energy could be used to drive the synthesis of ATP, how many moles of ATP could be formed from 1 mol of glucose?

23.66 What is the function of the protein F_1-ATPase?

23.67 According to the chemiosmotic theory, ATP synthesis results from the flow of what particles? Across what membrane does this flow occur?

The Complete Oxidation of Glucose (Section 23.8)

23.68 Explain why NADH produced in muscles during glycolysis ultimately gives rise to just 1.5 molecules of ATP.

23.69* A total of 32 mol of ATP can be produced by the complete oxidation of 1 mol of glucose in the liver. Indicate the number of these moles of ATP produced by:

- **a.** glycolysis
- **b.** the citric acid cycle
- **c.** the electron transport chain and oxidative phosphorylation

23.70 Refer to **Table 23.1**. A total of 32 mol of ATP can be produced by the complete oxidation of 1 mol of glucose in the liver. Indicate the number of these moles of ATP produced:

- **a.** From the oxidation of pyruvate to acetyl CoA
- **b.** From the cytoplasmic NADH formed during glycolysis
- **c.** When succinyl CoA changes to succinate in the citric acid cycle

23.71 The complete biochemical oxidation of glucose to ATP is only 34% efficient in capturing the total amount of energy released. The remaining 66% is released as what form of energy?

23.72 In terms of ATP production, compare the complete oxidation of glucose to CO_2 and H_2O with the anaerobic oxidation of glucose to lactate.

Glycogen Metabolism (Section 23.9)

23.73 Compare the terms *glycogenesis* and *glycogenolysis.*

23.74 Fructose and galactose from digested food enter the glycolysis pathway. Name the intermediates of the pathway which serve as entry points for these substances.

23.75 What is the reactant of the first step of glycogenesis, when the product of the reaction is glucose-1-phosphate?

23.76 Glucose 1-phosphate is the product of the first step of glycogenolysis. What is the reactant?

23.77 What high-energy compound is involved in the conversion of glucose to glycogen?

23.78 Why is it important that the liver store glycogen? How does this aid the controlling of blood sugar levels?

23.79* Why can liver glycogen, but not muscle glycogen, be used to raise blood sugar levels?

23.80 Explain why the liver has a capacity to supply free glucose to the blood, while neither the brain nor muscle cells have this capacity.

23.81 How does glycogen enter the glycolysis pathway?

Gluconeogenesis (Section 23.10)

23.82 What organ serves as the principal site for gluconeogenesis?

23.83 A friend has been fasting for three days. Where does the energy come from to keep his brain functioning?

23.84 What are the sources of compounds that undergo gluconeogenesis?

23.85 Explain what would happen to gluconeogenesis by the liver if your friend went on a diet totally free of carbohydrates, including all starches and sugars.

23.86 Explain the operation of the Cori cycle and its importance to muscles.

23.87 Lactate is considered to be a "dead-end" metabolite because it cannot be further oxidized for energy production. Explain how lactate is not wasted when it's made.

23.88 Would the Cori cycle operate if the body's muscles were completely oxidizing the glucose supplied? Why or why not?

The Hormonal Control of Carbohydrate Metabolism (Section 23.11)

23.89 What cells produce insulin and glucagon in the body?

23.90 Describe the influence of glucagon and insulin on the following:

- **a.** Blood sugar level
- **b.** Glycogen formation

23.91 Explain why it is important that the liver releases glucose into the blood stream during glycogenolysis.

23.92* Why is it more important that epinephrine stimulate the breakdown of glycogen in the muscles rather than elevating blood sugar levels?

23.93 Compare the target tissues for the hormones glucagon and epinephrine.

Additional Exercises

23.94 You eat a dextrose tablet that contains 10.0 g of glucose for an energy boost. How many molecules of ATP can be produced with the complete oxidation of this glucose by muscle cells?

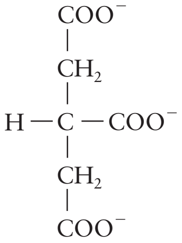
23.95 As an athlete's cells begin to go anaerobic, what happens to the rate of pyruvate oxidation by the citric acid cycle? What happens to the rate of glycolysis? Explain how each of these rate changes occurs and which enzymes are affected.

23.96 Lactate dehydrogenase catalyzes the following equilibrium reaction in both liver and muscle cells:

$$\text{pyruvate} + \text{NADH} + \text{H}^+ \leftrightarrows \text{lactate} + \text{NAD}^+$$

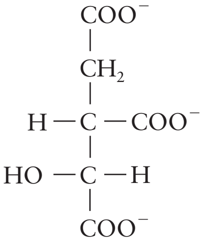
In terms of equilibrium, explain why lactate must be removed from muscle cells under anaerobic conditions and why lactate does not accumulate in the liver under these conditions. (*Hint*: Think of the Cori cycle.)

23.97 Identify all chiral carbon atoms in citrate and isocitrate.



$$\begin{array}{c} \text{COO}^- \\ | \\ \text{CH}_2 \\ | \\ \text{H}-\text{C}-\text{COO}^- \\ | \\ \text{CH}_2 \\ | \\ \text{COO}^- \end{array}$$

citrate



$$\begin{array}{c} \text{COO}^- \\ | \\ \text{CH}_2 \\ | \\ \text{H}-\text{C}-\text{COO}^- \\ | \\ \text{HO}-\text{C}-\text{H} \\ | \\ \text{COO}^- \end{array}$$

isocitrate

23.98 The pyruvate dehydrogenase enzyme complex becomes inactive when a specific serine residue in the enzyme complex is phosphorylated by ATP. Phosphorylation is the covalent addition of a phosphate group. Show how this reaction occurs and name the type of bond formed.

Chemistry for Thought

23.99 The citric acid cycle does not utilize oxygen, yet it cannot function without oxygen. Why?

23.100 Malonate ($^{-}\text{OOC—CH}_2\text{—COO}^{-}$) is an extremely effective competitive inhibitor of the citric acid cycle. Which enzyme do you think malonate inhibits? Explain.

23.101 A friend started to make wine by adding yeast to fresh grape juice and placing the mixture in a sealed bottle. Several days later the bottle exploded. Explain.

23.102 Two students are debating whether 30 or 32 molecules of ATP can be formed by the catabolism of one molecule of glucose. Who is correct?

23.103 Explain why monitoring blood lactate levels might be a useful technique to gauge the amount of conditioning in an Olympic runner.

23.104 You may have experienced a rush of epinephrine during a recent exam or athletic event. Are there other physiological responses to epinephrine in addition to a higher blood sugar level?

23.105 In **Figure 23.5**, it is noted that making bread involves a fermentation process. Why, then, is the alcohol content of bread zero?

23.106 A friend has the habit of eating four or five candy bars per day as snacks. What might be the metabolic consequences of such a practice?

23.107 List some pros and cons of a low-carbohydrate diet.

23.108 Cyanide is believed to act as an inhibitor of the electron transport chain. Why is such an inhibitor so toxic?

23.109 Drinking milk always seems to make you slightly nauseous. What might be an explanation for this?

24 Lipid and Amino Acid Metabolism

iStock.com/SDI Productions

Health Career Focus

PEDIATRIC NURSE

As a pediatric nurse at a gastroenterological clinic in a children's hospital, I provide care for children with all sorts of nutritional difficulties. Some arrive for inpatient bowel cleanouts, some for abdominal X-rays, others for feeding-tube placement. Some need periodic bloodwork to check that their metabolic levels are correct while taking their medications. Many come in with fasting protocols before their testing, and they aren't very happy.

I like to get down on the children's level, look them in the eye, and take the time to let them explain how they feel. You'd be surprised how they connect with you when they know you're talking to them and not their parent. They really appreciate the chance to express themselves. Sometimes, you get the shy ones and they prefer "talking" through playing with a toy, or drawing, but I can usually make a connection—that's the best part of my day.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Describe the digestion, absorption, and distribution of lipids in the body. **(Section 24.1)**
2. Explain what happens during fat mobilization. **(Section 24.2)**
3. Identify the metabolic pathway by which glycerol is catabolized. **(Section 24.3)**
4. Outline the steps of β-oxidation for fatty acids. **(Section 24.4)**
5. Determine the amount of ATP produced by the complete catabolism of a fatty acid. **(Section 24.5)**
6. Name the three ketone bodies and list the conditions that cause their overproduction. **(Section 24.6)**
7. Describe the pathway for fatty acid synthesis. **(Section 24.7)**
8. Describe the source and function of the body's amino acid pool. **(Section 24.8)**
9. Write equations for transamination and deamination reactions. **(Section 24.9)**

10 Explain the overall results of the urea cycle. **(Section 24.9)**

11 Describe how amino acids can be used for energy production, the synthesis of triglycerides, and gluconeogenesis. **(Section 24.10)**

12 State the relationship between intermediates of carbohydrate metabolism and the synthesis of nonessential amino acids. **(Section 24.11)**

TRIGLYCERIDES (FATS AND OILS) ARE IMPORTANT dietary sources of energy. Fat also functions as the major form of energy storage in humans. Fat, with a caloric value of 9 calories/g, contains more than twice the energy per gram of glycogen or starch. Thus, fat is a more concentrated and efficient storage form of energy than carbohydrates (see **Figure 24.1**). Because it is water-insoluble, fat can be stored in much larger quantities in our bodies. For example, the limited carbohydrate reserves in the body are depleted after about 1 day without food, but stored fat can provide needed calories (but not other nutrients) in an individual for 30 to 40 days. Amino acids perform three vital functions in the human body: They are the building blocks for the synthesis of proteins, they provide carbon and nitrogen atoms for the synthesis of other biomolecules, and they can be sources of energy.

In this chapter, we discuss the storage, degradation, and synthesis of lipids. We also study the degradation and synthesis of amino acids and the relationships between amino acid metabolism and the metabolism of carbohydrates and lipids.

Karel Bock/Shutterstock.com

FIGURE 24.1 When flying long distances, migrating geese use triglycerides (stored fat) as their major source of energy.

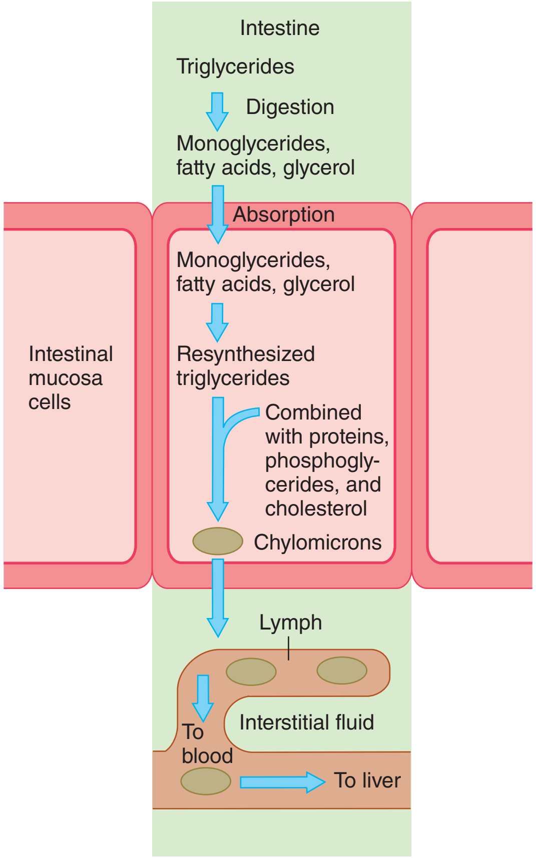
24.1 Blood Lipids

Learning Objective 1 Describe the digestion, absorption, and distribution of lipids in the body.

During digestion, triglycerides are hydrolyzed to glycerol, fatty acids, and monoglycerides (one fatty acid attached to glycerol). Phosphoglycerides are also hydrolyzed to their component substances. These smaller molecules, along with cholesterol, are absorbed into cells of the intestinal mucosa, where resynthesis of the triglycerides and phosphoglycerides occurs. For transport within the aqueous environment of the lymph and blood, these insoluble lipids are complexed with proteins to form lipoprotein aggregates called **chylomicrons**. The chylomicrons (which contain triglycerides, phosphoglycerides, and cholesterol) pass into the lymph system and then into the bloodstream. Chylomicrons are modified by the liver into smaller lipoprotein particles, the form in which most lipids are transported to various parts of the body by the bloodstream (see **Figure 24.2**).

chylomicron A lipoprotein aggregate found in the lymph and the bloodstream.

FIGURE 24.2 The digestion and absorption of triglycerides.


Intestine
Triglycerides
Digestion
Monoglycerides, fatty acids, glycerol
Absorption
Monoglycerides, fatty acids, glycerol
Intestinal mucosa cells
Resynthesized triglycerides
Combined with proteins, phosphoglycerides, and cholesterol
Chylomicrons
Lymph
Interstitial fluid
To blood
To liver

To some extent, the behavior of blood lipids parallels that of blood sugar. The concentration of both substances increases following a meal and returns to normal as a result of storage in fat depots and of oxidation to provide energy. As shown in **Figure 24.3**, the concentration of plasma lipids usually begins to rise within 2 hours after a meal, reaches a peak in 4 to 6 hours, and then drops rather rapidly to a normal level.

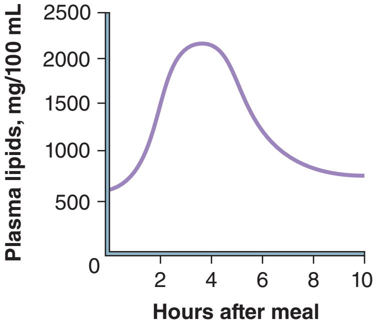


FIGURE 24.3 The rise in blood lipids following a meal containing fat.

One general method of classifying lipoproteins is by density. Because lipids are less dense than proteins, lipoprotein particles with a higher proportion of lipids are less dense than those with a lower proportion. Chylomicrons are the least dense because they have the highest ratio of lipid to protein. **Figure 24.4** is a schematic model of a low-density lipoprotein (LDL). The compositions of the four classes of lipoprotein are

HEALTH CONNECTIONS **24.1**

Are Certain Foods Better for the Brain?

When it comes to eating better for your brain, there are several foods and nutrients that may improve mood and memory and prevent age-related declines in cognitive function. Most research points to the so-called Mediterranean diet—one that is high in healthy fats, legumes, nuts, cereal, fish, fruits, and vegetables—as being the best for the brain. This dietary pattern, which is also lower in saturated fat and meat and contains moderate amounts of alcohol and dairy products, has several benefits when it comes to memory, cognitive function, and mood.

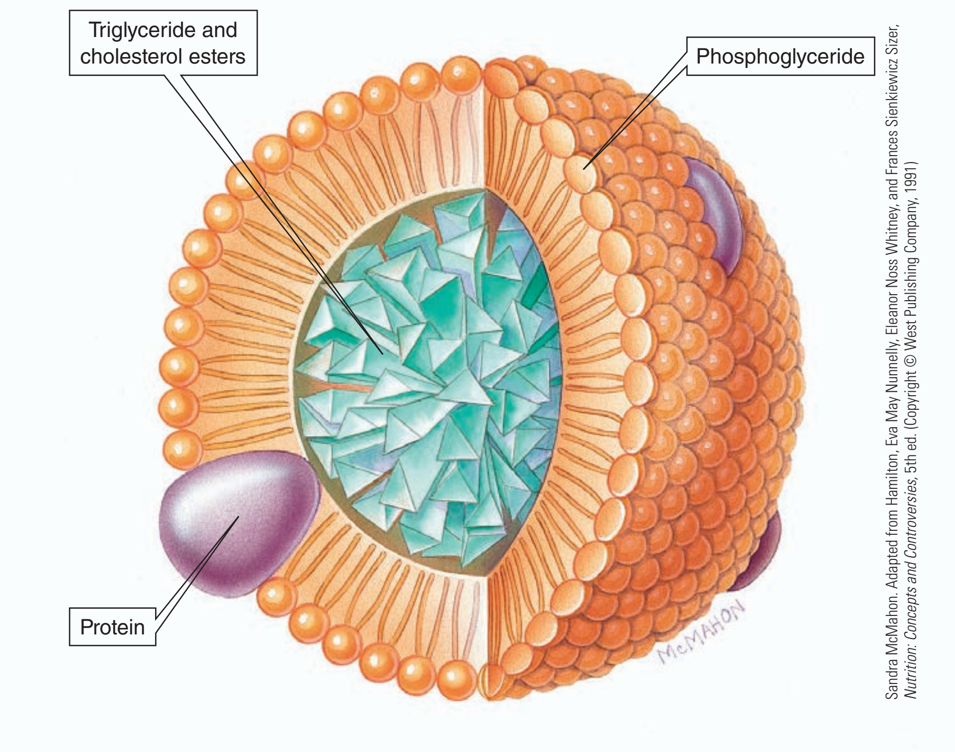
Research shows that higher levels of high-density lipoproteins (HDL) cholesterol, commonly referred to as "good" cholesterol, may play a role in the preservation of memory. Many of the key components of the Mediterranean diet—including replacing saturated fat with unsaturated fat, eating plenty of soluble fiber found in legumes and cereal, and moderate alcohol consumption—may also help support healthy HDL levels.

Nuts and seeds may also be particularly beneficial for the brain. Almonds and sunflower seeds are good sources of monounsaturated fat and vitamin E, an antioxidant that helps protect neuronal (brain cell) membranes. Neuronal membranes are lined with fat. Healthy dietary fats, like monounsaturated fat, may improve the binding of neurotransmitters to these membranes. Neurotransmitters allow brain cells to communicate with each other, and their improved binding might improve mood. Animal studies indicate that walnuts—rich in polyphenols, polyunsaturated fatty acids, and antioxidants—provide a potent brain boost.

The omega-3 fatty acid DHA (docosahexaenoic acid) is also an important component of neuronal membranes. DHA plays a key role in brain structure and function and may offer protection against age-related cognitive decline. Since our bodies do not produce DHA, it is considered an essential fatty acid and must be obtained from our diet. Fatty fish—including salmon, tuna, mackerel, herring, and sardines—are excellent sources of DHA and should be consumed at least twice per week. Research also suggests that higher intakes of fish may be linked to lower levels of depression.

Robyn Mackenzie/Shutterstock.com

DHA is present in salmon.



Sandra McMahon. Adapted from Hamilton, Eva May Nunnelly, Eleanor Noss Whitney, and Frances Sienkiewicz Sizer, *Nutrition: Concepts and Controversies*, 5th ed. (Copyright © West Publishing Company, 1991)

FIGURE 24.4 A schematic model of low-density lipoprotein (LDL).

compared in **Figure 24.5**. We see from **Figure 24.5** that the protein content of chylomicrons is significantly lower than that of other plasma lipoproteins, and that this low percentage results in a density of the particle that is less than 0.95 g/mL. Notice that the so-called HDL have a protein mass that is 45% to 50% of the total mass of the particles. The densities of HDL particles have correspondingly high values, ranging from 1.06 to 1.21 g/mL.

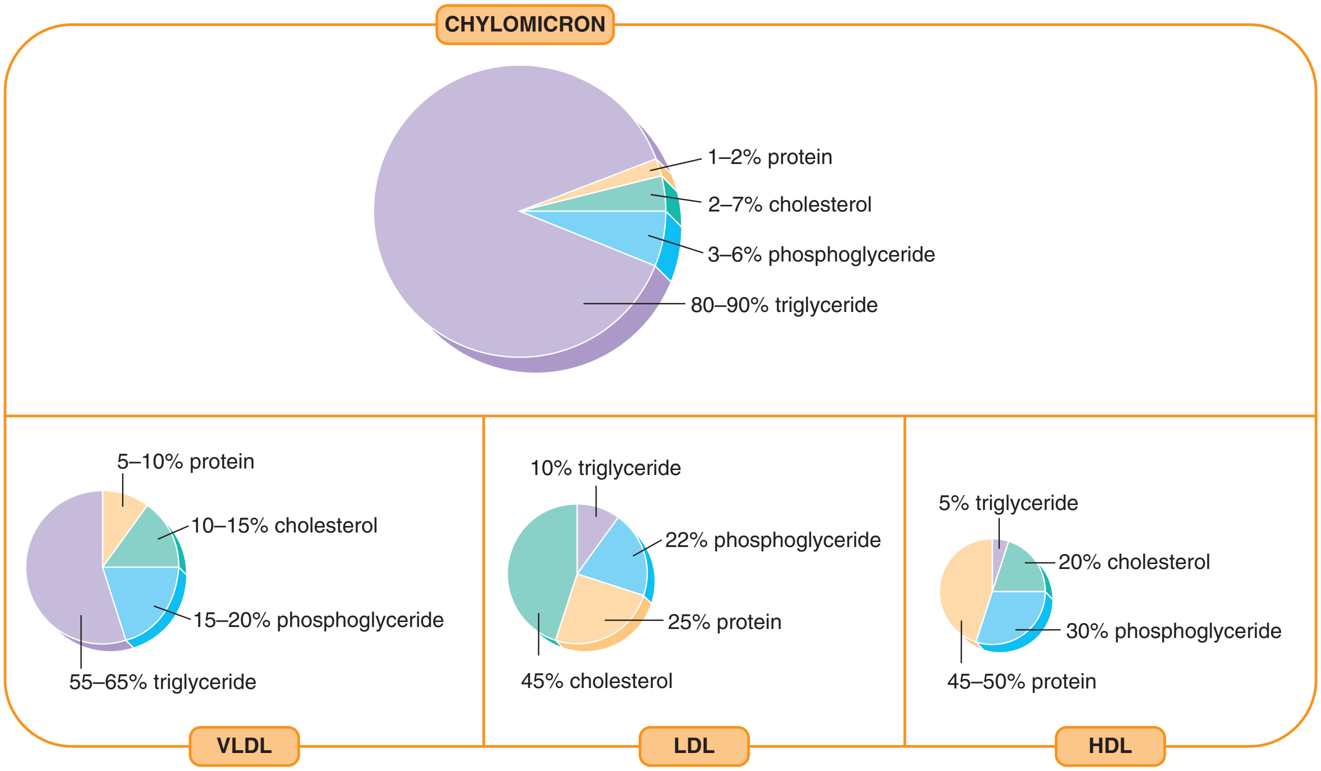


FIGURE 24.5 Relative amounts of cholesterol, protein, triglyceride, and phosphoglyceride in the four classes of lipoproteins. VLDL = very-low-density lipoprotein.

tookapic/1076 images/Pixabay

FIGURE 24.6 Marathon runners are initially fueled by glucose; triglycerides become the primary fuel in later stages of the race.

24.2 Fat Mobilization

Learning Objective 2 Explain what happens during fat mobilization.

Carbohydrates from dietary sources and glycogen catabolism are the compounds utilized preferentially for energy production by some tissues. The brain and active skeletal muscles are examples of such tissues. But as we have seen, the body's stores of glycogen are depleted after only a few hours of fasting. When this happens, fatty acids stored in triglycerides are called on as energy sources (see **Figure 24.6**). Even when glycogen supplies are adequate, many body cells, such as those of resting muscle and liver, utilize energy derived from the breakdown of fatty acids. This helps to conserve the body's glycogen stores and glucose for use by brain cells and red blood cells. Red blood cells cannot oxidize fatty acids because they have no mitochondria, the site of fatty acid oxidation. Brain cells are bathed in cerebrospinal fluid and do not obtain nutrients directly from the blood because of the blood-brain barrier. Glucose and many other substances can cross the barrier into the cerebrospinal fluid, but fatty acids cannot.

When body cells need fatty acids for energy, the endocrine system is stimulated to produce several hormones, including epinephrine, which interact with **adipose tissue**. Earlier we saw that epinephrine stimulates the conversion of glycogen to glucose. In the fat cells of adipose tissue, epinephrine stimulates the hydrolysis of triglycerides to fatty acids and glycerol, which enter the bloodstream. This process is called **fat mobilization**. In the

adipose tissue A kind of connective tissue where triglycerides are stored.

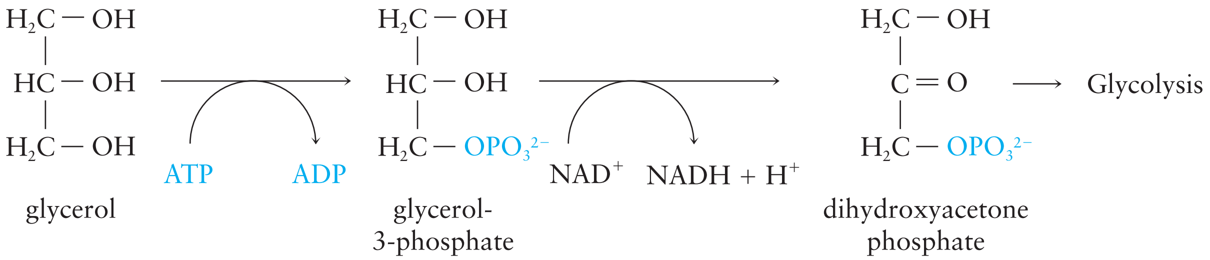
fat mobilization The hydrolysis of stored triglycerides, followed by the entry of fatty acids and glycerol into the bloodstream.

blood, mobilized fatty acids form a lipoprotein with the plasma protein called serum albumin. In this form, the fatty acids are transported to the tissue cells that need them. The glycerol produced by the hydrolysis of the triglyceride is water-soluble, so it dissolves in the blood and is also transported to cells that need it.

24.3 Glycerol Metabolism

Learning Objective 3 Identify the metabolic pathway by which glycerol is catabolized.

The glycerol hydrolyzed from fats can provide energy to cells. Glycerol is converted in the cytoplasm of the cell to dihydroxyacetone phosphate in two steps:



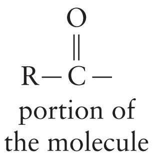
(24.1)

Dihydroxyacetone phosphate is one of the chemical intermediates of glycolysis (see **Section 23.3**). Thus, glycerol, by entering glycolysis, can be converted to pyruvate and contribute to cellular energy production. The pyruvate formed from glycerol can also be converted to glucose through gluconeogenesis (see **Section 23.10**).

24.4 The Oxidation of Fatty Acids

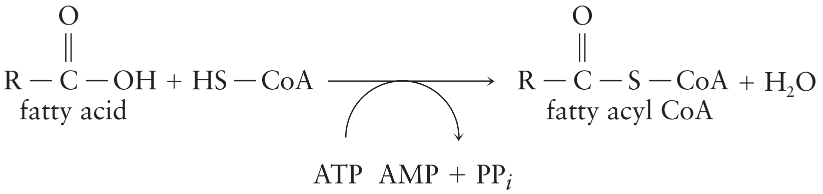
Learning Objective 4 Outline the steps of β-oxidation for fatty acids.

Fatty acids that enter tissue cells cannot be oxidized to produce energy until they pass through the mitochondrial membrane. This cannot occur until the fatty acid is converted into fatty acyl CoA by reaction with coenzyme A. Fatty acyl refers to the



$$R-\overset{O}{\overset{\|}{C}}-$$

portion of the molecule



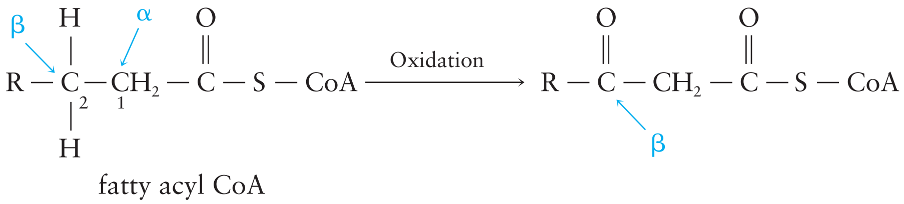
$$R-\overset{O}{\overset{\|}{C}}-OH + HS-CoA \xrightarrow[\text{ATP}\quad \text{AMP} + PP_i]{} R-\overset{O}{\overset{\|}{C}}-S-CoA + H_2O$$

(24.2)

This reaction, which is catalyzed by acyl CoA synthetase, is referred to as activation of the fatty acid because the fatty acyl CoA is a high-energy compound. The energy needed for its synthesis is provided by the hydrolysis of ATP to AMP and PP_i and the subsequent hydrolysis of PP_i to $2P_i$. The process of forming fatty acyl CoA molecules demonstrates how the energy stored in the phosphate bonds of ATP can be used to drive chemical processes that normally could not occur. The cost to the cell of activating one molecule of fatty acid is the loss of two high-energy bonds in an ATP molecule.

The fatty acyl CoA molecules that enter mitochondria are then degraded in a catabolic process called **β-oxidation**. During β-oxidation, the second (or beta) carbon down the chain from the carbonyl of the fatty acyl CoA molecule is oxidized to a ketone:

β-oxidation process A pathway in which fatty acids are broken down into molecules of acetyl CoA.

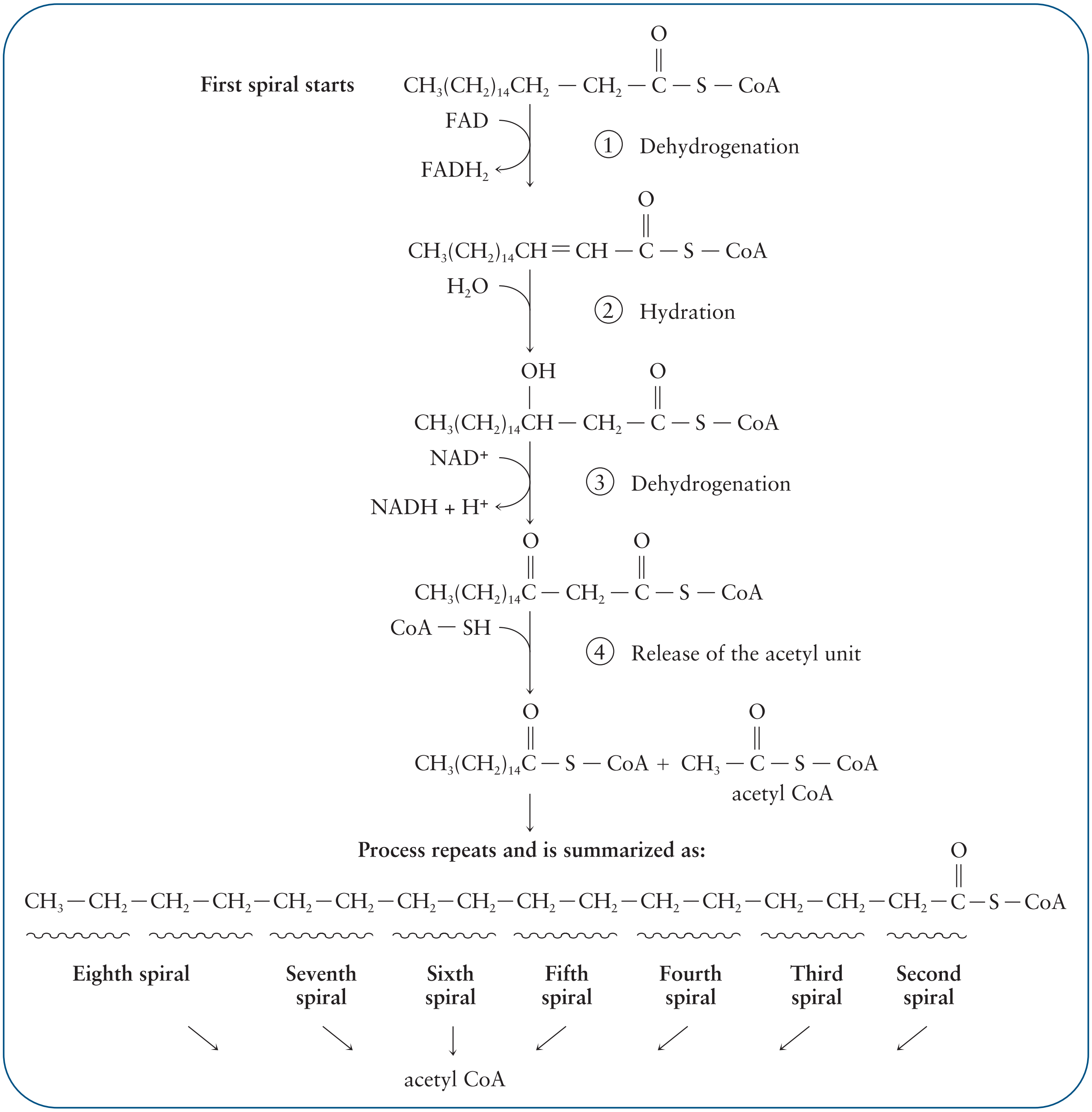


$$R-\underset{H}{\overset{H}{C}}-CH_2-\overset{O}{\overset{\|}{C}}-S-CoA \xrightarrow{\text{Oxidation}} R-\overset{O}{\overset{\|}{C}}-CH_2-\overset{O}{\overset{\|}{C}}-S-CoA$$

(24.3)

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

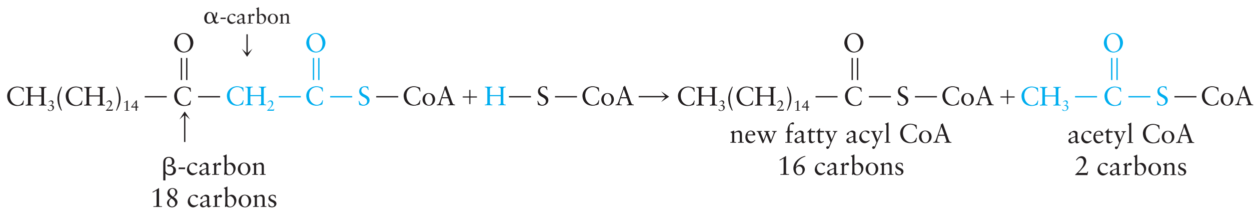
Four reactions are involved in oxidizing the β-carbon to a ketone. We will use the fatty acyl CoA formed from one 18-carbon acid, stearic acid, as an example of the reactions. We will also keep track of any NADH or $FADH_2$ produced in the reactions because these molecules can enter the respiration process (electron transport chain). The reactions involved in β-oxidation are shown in **Figure 24.7**.



First spiral starts
$CH_3(CH_2)_{14}CH_2-CH_2-C(=O)-S-CoA$
FAD
$FADH_2$
① Dehydrogenation
$CH_3(CH_2)_{14}CH=CH-C(=O)-S-CoA$
H_2O
② Hydration
$CH_3(CH_2)_{14}CH(OH)-CH_2-C(=O)-S-CoA$
NAD^+
$NADH + H^+$
③ Dehydrogenation
$CH_3(CH_2)_{14}C(=O)-CH_2-C(=O)-S-CoA$
CoA — SH
④ Release of the acetyl unit
$CH_3(CH_2)_{14}C(=O)-S-CoA + CH_3-C(=O)-S-CoA$
acetyl CoA
Process repeats and is summarized as:
$CH_3-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-C(=O)-S-CoA$
Eighth spiral
Seventh spiral
Sixth spiral
Fifth spiral
Fourth spiral
Third spiral
Second spiral
acetyl CoA

FIGURE 24.7 The fatty acid spiral: β-oxidation of stearic acid.

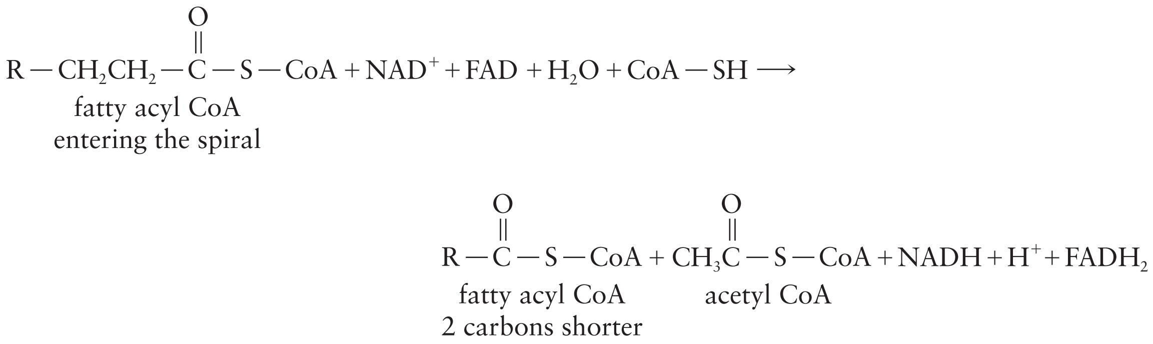
In the final step of β-oxidation (Step 4), the chain is broken between the α- and β-carbons by reaction with coenzyme A. As a result, a new fatty acyl CoA is formed with a chain shortened by two carbon atoms, and a unit of acetyl CoA is released:



$$\mathrm{CH_3(CH_2)_{14}}-\underset{\substack{\uparrow\\ \beta\text{-carbon}\\ \text{18 carbons}}}{\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}}-\overset{\substack{\alpha\text{-carbon}\\ \downarrow}}{\mathrm{CH_2}}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{S}-\mathrm{CoA}+\mathrm{H}-\mathrm{S}-\mathrm{CoA}\longrightarrow \underset{\substack{\text{new fatty acyl CoA}\\ \text{16 carbons}}}{\mathrm{CH_3(CH_2)_{14}}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{S}-\mathrm{CoA}}+\underset{\substack{\text{acetyl CoA}\\ \text{2 carbons}}}{\mathrm{CH_3}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{S}-\mathrm{CoA}} \qquad (24.4)$$

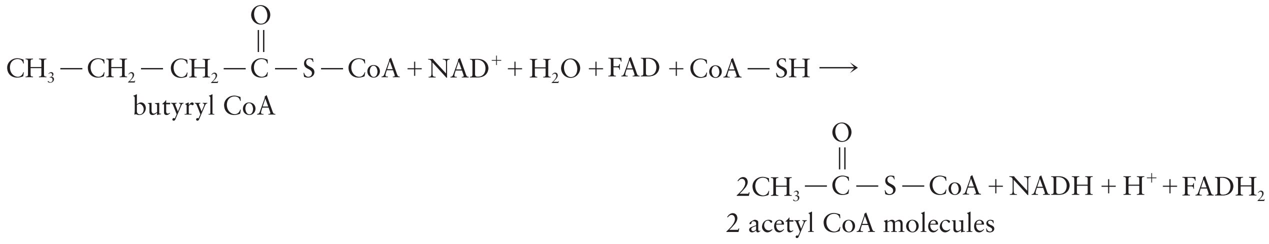
The new fatty acyl compound enters the β-oxidation process at Step 1, and the sequence is repeated until the fatty acyl CoA is completely degraded to acetyl CoA (see **Figure 24.7**). The fatty acyl CoA molecule that starts each run through the β-oxidation process is two carbons shorter than the one going through the previous run. For this reason, the β-oxidation pathway for fatty acid degradation to acetyl CoA is often called the fatty acid spiral (rather than cycle).

Every run through the spiral produces one molecule each of acetyl CoA, NADH, and $FADH_2$ until the fatty acyl CoA is only four carbons long:



$$\underset{\substack{\text{fatty acyl CoA}\\ \text{entering the spiral}}}{\mathrm{R}-\mathrm{CH_2CH_2}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{S}-\mathrm{CoA}}+\mathrm{NAD^+}+\mathrm{FAD}+\mathrm{H_2O}+\mathrm{CoA}-\mathrm{SH}\longrightarrow \underset{\substack{\text{fatty acyl CoA}\\ \text{2 carbons shorter}}}{\mathrm{R}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{S}-\mathrm{CoA}}+\underset{\text{acetyl CoA}}{\mathrm{CH_3}\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{S}-\mathrm{CoA}}+\mathrm{NADH}+\mathrm{H^+}+\mathrm{FADH_2} \qquad (24.5)$$

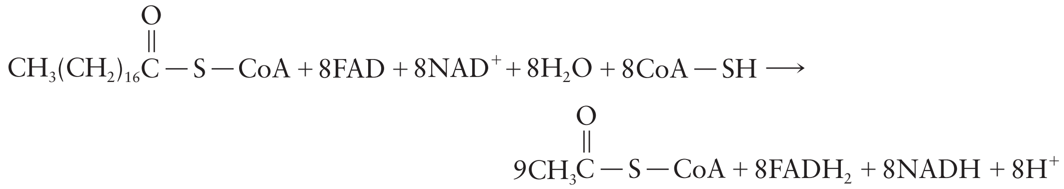
In the last spiral, the four-carbon chain of butyryl CoA passes through the β-oxidation sequence, and it produces one molecule of $FADH_2$, one molecule of NADH, and two molecules of acetyl CoA:



$$\underset{\text{butyryl CoA}}{\mathrm{CH_3}-\mathrm{CH_2}-\mathrm{CH_2}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{S}-\mathrm{CoA}}+\mathrm{NAD^+}+\mathrm{H_2O}+\mathrm{FAD}+\mathrm{CoA}-\mathrm{SH}\longrightarrow \underset{\text{2 acetyl CoA molecules}}{2\mathrm{CH_3}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{S}-\mathrm{CoA}}+\mathrm{NADH}+\mathrm{H^+}+\mathrm{FADH_2} \qquad (24.6)$$

In other words, the complete conversion of a fatty acyl CoA to two-carbon fragments of acetyl CoA always produces one more molecule of acetyl CoA than of $FADH_2$ or NADH. Thus, the breakdown of stearic acid requires eight passes through the β-oxidation sequence and produces 9 molecules of acetyl CoA, but only 8 molecules of $FADH_2$ and 8 molecules of NADH.

Net reaction:



$$\mathrm{CH_3(CH_2)_{16}}\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{S}-\mathrm{CoA}+8\mathrm{FAD}+8\mathrm{NAD^+}+8\mathrm{H_2O}+8\mathrm{CoA}-\mathrm{SH}\longrightarrow 9\mathrm{CH_3}\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{S}-\mathrm{CoA}+8\mathrm{FADH_2}+8\mathrm{NADH}+8\mathrm{H^+} \qquad (24.7)$$

Example 24.1 Calculations Involving Fatty Acids

Dodecanoic acid (12 carbon atoms) is converted to acetyl CoA through β-oxidation. What are the yields of the following?

a. acetyl CoA
b. $FADH_2$
c. NADH

Solution

a. Each acetyl CoA contains two carbon atoms from dodecanoic acid. Thus, six acetyl CoA molecules are formed.
b. Twelve carbon atoms require five trips through the fatty acid spiral. Thus, five molecules of $FADH_2$ are formed.
c. Five trips through the spiral also produce five NADH molecules and five H^+ ions.

✔ **LEARNING CHECK 24.1** Capric acid (10 carbon atoms) is converted to acetyl CoA through β-oxidation. What are the yields of the following?

a. acetyl CoA b. $FADH_2$ c. NADH

24.5 The Energy from Fatty Acids

Learning Objective 5 Determine the amount of ATP produced by the complete catabolism of a fatty acid.

To compare the energy yield from fatty acids with that from glucose, let's continue our discussion with stearic acid, a typical and abundant fatty acid.

We start with the activation of stearic acid by reacting it with coenzyme A to form stearoyl CoA. The energy needed to cause this reaction to occur comes from the hydrolysis of ATP to AMP and PP_i and the subsequent hydrolysis of PP_i to $2P_i$. This is equivalent to hydrolyzing two molecules of ATP to ADP.

As a stearoyl CoA molecule (18 carbons) passes through the β-oxidation spiral, 9 acetyl CoA, 8 $FADH_2$, and 8 NADH molecules are produced. Acetyl CoA produced in the fatty acid spiral can enter the citric acid cycle (followed by the electron transport chain), where each molecule of acetyl CoA results in the production of 10 ATP molecules. In addition, when the $FADH_2$ and NADH molecules enter the electron transport chain, each $FADH_2$ yields 1.5 ATP molecules, and each NADH yields 2.5 molecules. The calculations are summarized in **Table 24.1**, which shows a total of 120 molecules of ATP formed from the 18-carbon fatty acid.

TABLE 24.1 Energy Produced by the Oxidation of Stearic Acid

Oxidation Product or Step	ATP/Unit	Total ATP
Activation step		−2
9 acetyl CoA	10.0	90
8 $FADH_2$	1.5	12
8 ($NADH + H^+$)	2.5	20
Total ATP from the 18-carbon fatty acid		120

It is instructive to compare the energy yield from the complete oxidation of fatty acids with that obtained from an equivalent amount of glucose, because both are important constituents of the diet. In **Section 23.8**, we saw that the oxidation of a single glucose molecule produces 32 ATP molecules. The complete oxidation of three 6-carbon glucose molecules (18 carbons) yields 3 × 32, or 96, ATP molecules. Thus, on the basis of equal numbers of carbons, lipids are nearly 25% more efficient than carbohydrates as energy-storage systems.

On a mass basis, the difference is even more striking. One mole of stearic acid weighs 284 g, and, as we have seen, it yields 120 mol of ATP on complete degradation. Three moles of glucose weigh 540 g and yield 96 mol of ATP. On this basis, 284 g of glucose would generate 50 mol of ATP. On an equal-mass basis, lipids contain more than twice the energy of carbohydrates. The reason for this difference is that fatty acids are a more reduced form of fuel, with a number of $—CH_2—$ groups as plentiful sources of H atoms for the energy-yielding oxidation process. Glucose, in contrast, is already partially oxidized, with an oxygen atom located on each carbon atom.

Example 24.2 Calculating ATP Production

Calculate the number of molecules of ATP produced by the complete oxidation of dodecanoic acid (12 carbon atoms) to carbon dioxide and water.

Solution

A 12-carbon fatty acid would yield six molecules of acetyl CoA; five trips through the spiral are necessary and would produce 5 $FADH_2$ and 5 NADH + 5 H^+.

$$
\begin{array}{lrl}
\text{6 acetyl CoA} \times \text{10 ATP/acetyl CoA} & = & 60 \ \text{ATP} \\
5\ \mathrm{FADH_2} \times 1.5\ \mathrm{ATP/FADH_2} & = & 7.5\ \text{ATP} \\
5\ \text{NADH} \times 2.5\ \text{ATP/NADH} & = & \underline{12.5\ \text{ATP}} \\
 & & 80 \ \text{ATP}
\end{array}
$$

✔ **LEARNING CHECK 24.2** Calculate the number of molecules of ATP produced by the complete oxidation of palmitic acid (16 carbon atoms) to carbon dioxide and water.

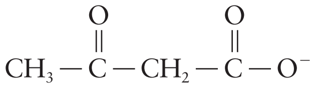
24.6 Ketone Bodies

Learning Objective 6 Name the three ketone bodies and list the conditions that cause their overproduction.

It is generally agreed by nutrition scientists that a diet balanced in carbohydrates and fats as energy sources is best for good health. When such a balanced diet is followed, most of the acetyl CoA produced by fatty acid metabolism is processed through the citric acid cycle.

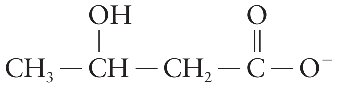
Under certain conditions, the balance between carbohydrate and fatty acid metabolism is lost. During a fast, for example, fatty acids from stored fats become the body's primary energy source. With a minimum amount of cellular glucose available, the level of glycolysis decreases, and a reduced amount of oxaloacetate is synthesized. In addition, oxaloacetate is used for gluconeogenesis to a greater-than-normal extent as the cells react to make their own glucose. The lack of oxaloacetate reduces the activity of the citric acid cycle. As a result of these events, more acetyl CoA is produced by fatty acid oxidation than can be processed through the citric acid cycle. As the concentration of acetyl CoA builds up, the excess is converted within the liver to three substances called **ketone bodies**—acetoacetate, β-hydroxybutyrate, and acetone.

ketone bodies Three compounds—acetoacetate, β-hydroxybutyrate, and acetone—formed from acetyl CoA.



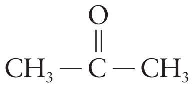
$$\mathrm{CH_3{-}\overset{\overset{O}{\|}}{C}{-}CH_2{-}\overset{\overset{O}{\|}}{C}{-}O^-}$$

acetoacetate



$$\mathrm{CH_3{-}\overset{\overset{OH}{|}}{CH}{-}CH_2{-}\overset{\overset{O}{\|}}{C}{-}O^-}$$

β-hydroxybutyrate
(not a ketone)



$$\mathrm{CH_3{-}\overset{\overset{O}{\|}}{C}{-}CH_3}$$

acetone

The ketone bodies are carried by the blood to body tissues—mainly the brain, heart, and skeletal muscle—where they may be oxidized to meet energy needs (see **Figure 24.8**). You can see from their structural formulas that β-hydroxybutyrate does not actually contain a ketone group, but it is nevertheless included in the designation because it is always produced along with the other two. Under normal conditions, the concentration of ketone bodies in the blood averages a very low 0.5 mg/100 mL (see **Figure 24.9**).

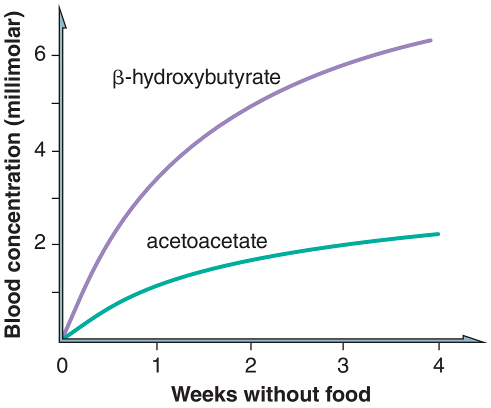


FIGURE 24.8 The effect of starvation on blood levels of β-hydroxybutyrate and acetoacetate.

Dr. P. Marazzi/Science Source

FIGURE 24.9 The level of ketone bodies in urine can be measured using a test strip.

Example 24.3 Describing Ketone Bodies

Three substances are referred to as ketone bodies.

a. Which ketone body is actually a ketone?
b. Which ketone body has an alcohol group?

Solution

a. Acetone
b. β-hydroxybutyrate

✔ **LEARNING CHECK 24.3** Which two ketone bodies are acidic?

ketonemia An elevated level of ketone bodies in the blood.

ketonuria The presence of ketone bodies in the urine.

acetone breath A condition in which acetone can be detected in the breath.

ketosis A condition in which ketonemia, ketonuria, and acetone breath exist together.

Diabetes mellitus, like a long fast or starvation, also produces an imbalance in carbohydrate and lipid metabolism. Even though blood glucose reaches hyperglycemic levels, a deficiency of insulin prevents the glucose from entering tissue cells in sufficient amounts to meet cellular energy needs. The resulting increase in fatty acid metabolism leads to excessive production of acetyl CoA and a substantial increase in the level of ketone bodies in the blood of poorly controlled diabetes. A concentration higher than about 20 mg/100 mL of blood is called **ketonemia** ("ketones in the blood"). At a level of about 70 mg/100 mL of blood, the renal threshold for ketone bodies is exceeded, and ketone bodies are excreted in the urine. This condition is called **ketonuria** ("ketones in the urine"). A routine check of urine for ketone bodies is useful in the diagnosis of diabetes. Occasionally, the concentration of acetone in the blood reaches levels that cause it to be expelled through the lungs, and the odor of acetone can be detected on the breath. When ketonemia, ketonuria, and **acetone breath** exist simultaneously, the condition is called **ketosis**.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

STUDY TOOLS 24.1

Key Numbers for ATP Calculations

The calculation of the energy yield in terms of ATP molecules from the metabolism of a fatty acid is a useful exercise because it may help you better understand this metabolic process. The three key substances to account for in such calculations are acetyl CoA, NADH, and $FADH_2$. Two carbon atoms must be transported by coenzyme A in order to synthesize acetyl CoA; thus, the number of acetyl CoA molecules formed is determined by the following equation:

$$\text{acetyl CoA} = \frac{\text{number of fatty acid carbons}}{2}$$

For example, a 10-carbon fatty acid would produce 10/2, or 5, acetyl CoA molecules.

Every trip through the fatty acid spiral produces one $NADH + H^+$ molecule and one $FADH_2$ molecule. Thus,

$$\text{number of trips} = \text{molecules NADH} = \text{molecules } FADH_2$$

Furthermore, the number of trips equals one less than the number of acetyl CoA molecules produced (because the last trip of the spiral produces 2 molecules of acetyl CoA). Thus, for the 10-carbon fatty acid above, 5 acetyl CoA molecules are produced during four trips through the spiral. Also, the four trips produce 4 $NADH + H^+$ molecules and 4 $FADH_2$ molecules.

Finally, remember the multipliers: Every acetyl CoA gives rise to 10 ATPs, every NADH produces 2.5 ATPs, and every $FADH_2$ gives 1.5 ATPs. The summary for the 10-carbon fatty acid is:

(5 acetyl CoA) × 10 = 50 ATP
$(4\ NADH + H^+) \times 2.5$ = 10 ATP
$(4\ FADH_2) \times 1.5$ = 6 ATP
Activation step = −2 ATP
Total ATP = 64 ATP

Two of the ketone bodies are acids, and their accumulation in the blood as ketosis worsens results in a condition of **acidosis** called **ketoacidosis** because it is caused by ketone bodies in the blood. If ketoacidosis is not controlled, the person becomes severely dehydrated because the kidneys excrete excessive amounts of water in response to low blood pH. Prolonged ketoacidosis leads to general debilitation, coma, and even death.

acidosis A low blood pH.

ketoacidosis A low blood pH due to elevated levels of ketone bodies.

Patients suffering from diabetes-related ketosis are usually given insulin as a first step in their treatment. The insulin restores normal glucose metabolism and reduces the rate of formation of ketone bodies. If the patient is also suffering severe dehydration, the return to fluid and acid–base balance is sped up by the intravenous administration of solutions containing sodium bicarbonate. Excessive alcohol consumption can also cause ketone bodies to be produced with acetone on the breath.

24.7 Fatty Acid Synthesis

Learning Objective 7 Describe the pathway for fatty acid synthesis.

When organisms (including humans) take in more nutrients than are needed for energy requirements, the excesses are not excreted; they are converted first to fatty acids and then to body fat (see **Figure 24.10**). Most of the conversion reactions take place in the liver, adipose tissue, and mammary glands. The mammary glands become especially active in the process during lactation.

Nancy Bauer/Shutterstock.com

FIGURE 24.10 The results of dietary excess.

As is true in the opposing processes of glycolysis and gluconeogenesis, the pathways for the opposing processes of fatty acid degradation and fatty acid synthesis are not simply the reverse of each other. The processes are separate from each other, utilize different enzyme systems, and are even located in different cellular compartments. Degradation by the β-oxidation pathway takes place in cellular mitochondria, whereas biosynthesis of fatty acids occurs in the cytoplasm.

However, one aspect of fatty acid synthesis and fatty acid degradation is the same. Both processes require units of two carbon atoms as a result of involving acetyl CoA. Thus, fatty acid chains are built up two carbons at a time during synthesis and broken down two carbons at a time during β-oxidation.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

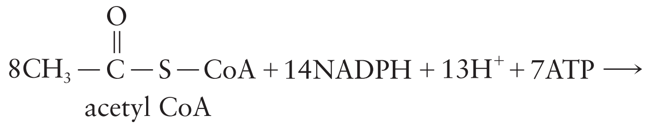
Acetyl CoA is generated inside mitochondria and so must be transported into the cytoplasm if it is to be used to synthesize fatty acids. This transport is done by first reacting acetyl CoA with oxaloacetate (the first step of the citric acid cycle). The product is citrate:

$$\text{acetyl CoA} + \text{oxaloacetate} + H_2O \longrightarrow \text{citrate} + \text{CoA—SH} \qquad (24.8)$$

Mitochondrial membranes contain a citrate transport system that enables excess citrate to move out of the mitochondria into the cytoplasm. Once in the cytoplasm, the citrate reacts to regenerate acetyl CoA and oxaloacetate.

Fatty acid synthesis occurs by way of a rather complex series of reactions catalyzed by a multienzyme complex called the *fatty acid synthetase system*. This system is made up of six enzymes and an additional protein, acyl carrier protein (ACP), to which all intermediates are attached.

The summary equation for the synthesis of palmitic acid from acetyl CoA demonstrates that a great deal of energy, 7 ATP + 14 NADPH (a phosphate derivative of NADH), is required:



$$\underset{\text{acetyl CoA}}{8CH_3-\overset{\overset{\displaystyle O}{\|}}{C}-S-CoA} + 14NADPH + 13H^+ + 7ATP \longrightarrow \qquad (24.9)$$

$$\text{(continued)} \quad \underset{\text{palmitate}}{CH_3(CH_2)_{14}COO^-} + 8CoA-SH + 6H_2O + 14NADP^+ + 7ADP + 7P_i$$

This large input of energy is stored in the synthesized fatty acids and is one of the reasons it is so difficult to lose excess weight due to fat. After synthesis, the fatty acids are incorporated into triglycerides and stored in the form of fat in adipose tissues.

The liver is the most important organ involved in fatty acid and triglyceride synthesis. It is able to modify body fats by lengthening or shortening and saturating or unsaturating the fatty acid chains. The only fatty acids that cannot be synthesized by the body are those that are polyunsaturated. However, linoleic acid (two double bonds) and linolenic acid (three double bonds) from the diet can be converted to other polyunsaturated fatty acids. This utilization of linoleic and linolenic acids as sources of other polyunsaturated fatty acids is the basis for classifying them as essential fatty acids for humans (see **Section 18.2**).

The human body can convert glucose to fatty acids, but it cannot convert fatty acids to glucose. Our cells contain no enzyme that can catalyze the conversion of acetyl CoA to pyruvate, a compound required for gluconeogenesis (see **Figure 23.14**). However, plants and some bacteria do possess such enzymes and convert fats to carbohydrates as part of their normal metabolism.

24.8 Amino Acid Metabolism

Learning Objective 8 Describe the source and function of the body's amino acid pool.

In terms of amount used, the most important function of amino acids is to provide building blocks for the synthesis of proteins in the body. It is estimated that about 75% of amino acid utilization in a normal, healthy adult is for this function. The maintenance of body proteins must occur constantly in the body because tissue proteins break down regularly from normal wear and tear, as well as from diseases and injuries. The amino acids used in this maintenance come from proteins that are eaten and hydrolyzed during digestion, from the body's own degraded tissue, and from the synthesis in the liver of certain amino acids. The amino acids from these three sources constitute what is called the **amino acid pool** of the body. This cellular supply of amino acids is constantly being restocked to allow the synthesis of new proteins and other necessary metabolic processes to take place as needed.

amino acid pool The total supply of amino acids in the body.

The dynamic process in which body proteins are continuously hydrolyzed and resynthesized is called **protein turnover**. The turnover rate, or life expectancy, of body proteins is a measure of how fast the proteins are broken down and resynthesized. The turnover rate is usually expressed as a half-life. The use of radioactive amino acids has enabled researchers to

protein turnover The continuing process in which body proteins are hydrolyzed and resynthesized.

estimate half-lives by measuring the exchange rate between body proteins and the amino acid pool. For example, the half-life of liver proteins is about 10 days. This means that over a 10-day period, half the proteins in the liver are hydrolyzed to amino acids and replaced by equivalent proteins. Plasma proteins also have a half-life of about 10 days, hemoglobin about 120 days, and muscle protein about 180 days. The half-life of collagen, a protein of connective tissue, is considerably longer—some estimates are as high as 1000 days. Other proteins, particularly enzyme and polypeptide hormones, have much shorter half-lives of only a few minutes. Once it is released from the pancreas, insulin has a half-life estimated to be only 7 to 10 minutes.

Because of the high turnover rate of proteins in the body, manufactured proteins do not have enough time to become a permanent part of the body structure or function. The frequent turnover of proteins is advantageous, for it allows the body to continually renew important molecules and to respond quickly to its own changing needs.

In addition to tissue protein synthesis, there is a constant draw on the amino acid pool for the synthesis of other nitrogen-containing biomolecules. These molecules include the purine and pyrimidine bases of nucleic acids; heme structures for hemoglobin and myoglobin; choline and ethanolamine, which are the building blocks of phospholipids; and neurotransmitters such as acetylcholine and dopamine. Like proteins, these compounds are also constantly being degraded and replaced. **Table 24.2** lists some of the important nitrogen-containing compounds that are synthesized from amino acids.

TABLE 24.2 Compounds Derived from Amino Acids

Amino Acid	Product	Function
Tyrosine	dopamine	Neurotransmitter
	norepinephrine	Neurotransmitter, hormone
	epinephrine	Hormone
	thyroxine (T_3 & T_4)	Hormone
	melanin	Skin pigmentation
Tryptophan	serotonin	Neurotransmitter
Histidine	histamine	Involved in allergic reactions
Serine	ethanolamine	Required in cephalin synthesis
Cysteine	taurine	A compound of bile salts

Unlike carbohydrates and fatty acids, amino acids in excess of immediate body requirements cannot be stored for later use. They are degraded and, depending on the organism, their nitrogen atoms are converted to either ammonium ions, urea, or uric acid and excreted. Their carbon skeletons are converted to pyruvate, acetyl CoA, or one of the intermediates of the citric acid cycle and used for energy production, the synthesis of glucose through gluconeogenesis (see **Section 23.10**), or conversion to triglycerides. The various pathways involved in amino acid metabolism are summarized in **Figure 24.11**.

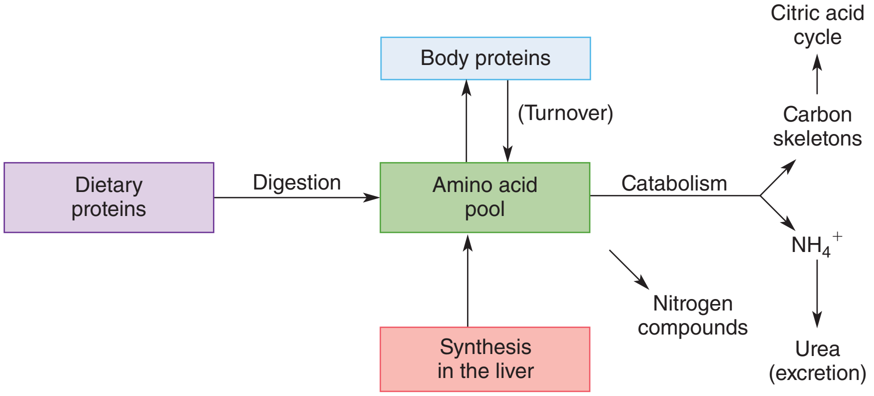


FIGURE 24.11 The major metabolic pathways of amino acids.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

24.9 Amino Acid Catabolism: The Fate of the Nitrogen Atoms

Learning Objective 9 Write equations for transamination and deamination reactions.

Learning Objective 10 Explain the overall results of the urea cycle.

As previously noted, excess amino acids cannot be stored in the body but are catabolized for energy production, and the nitrogen is either excreted or used to synthesize other nitrogen-containing compounds. In this section, we will study the chemical pathways involved with the nitrogen. The chemical fate of the carbon skeleton of the amino acids is discussed in **Section 24.10**.

In essence, there are three stages in nitrogen catabolism (see **Figure 24.12**). These processes (which occur in the liver) are transamination, deamination, and urea formation.

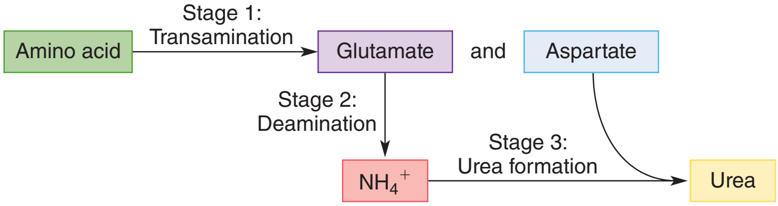


FIGURE 24.12 An overview of the catabolic fate of nitrogen atoms in amino acids.

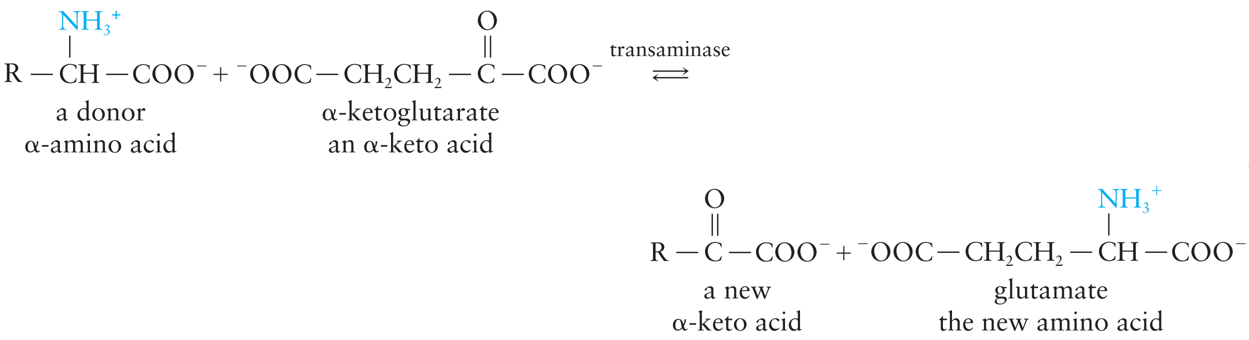
24.9A Stage 1: Transamination

transaminase An enzyme that catalyzes the transfer of an amino group.

transamination The enzyme-catalyzed transfer of an amino group to a keto acid.

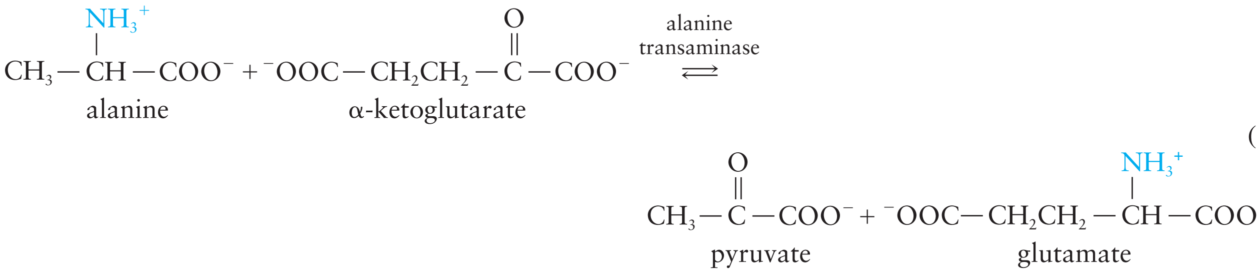
In the tissues, amino groups freely move from one amino acid to another under the catalytic influence of enzymes called aminotransferases, or more commonly, **transaminases**. A key reaction for amino acids undergoing catabolism is a **transamination** involving the transfer of amino groups to α-ketoglutarate. The carbon skeleton of the amino acid remains behind and is transformed into a new α-keto acid:

General reaction:



$$\underset{\substack{\text{a donor}\\ \alpha\text{-amino acid}}}{R-\overset{\overset{NH_3^+}{|}}{C}H-COO^-} + \underset{\substack{\alpha\text{-ketoglutarate}\\ \text{an }\alpha\text{-keto acid}}}{{}^-OOC-CH_2CH_2-\overset{\overset{O}{\|}}{C}-COO^-} \xrightleftharpoons{\text{transaminase}} \underset{\substack{\text{a new}\\ \alpha\text{-keto acid}}}{R-\overset{\overset{O}{\|}}{C}-COO^-} + \underset{\substack{\text{glutamate}\\ \text{the new amino acid}}}{{}^-OOC-CH_2CH_2-\overset{\overset{NH_3^+}{|}}{C}H-COO^-} \quad (24.10)$$

Specific example:



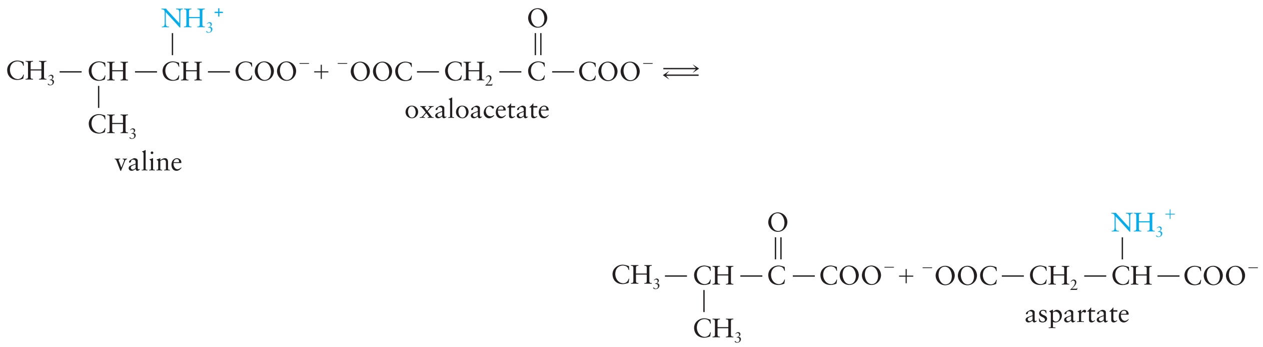
$$\underset{\text{alanine}}{CH_3-\overset{\overset{NH_3^+}{|}}{C}H-COO^-} + \underset{\alpha\text{-ketoglutarate}}{{}^-OOC-CH_2CH_2-\overset{\overset{O}{\|}}{C}-COO^-} \xrightleftharpoons{\substack{\text{alanine}\\ \text{transaminase}}} \underset{\text{pyruvate}}{CH_3-\overset{\overset{O}{\|}}{C}-COO^-} + \underset{\text{glutamate}}{{}^-OOC-CH_2CH_2-\overset{\overset{NH_3^+}{|}}{C}H-COO^-} \quad (24.11)$$

Notice that in the reaction, the $-NH_3^+$ group trades places with a carbonyl oxygen.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

A second important example of transamination is the production of aspartate, which is used in Stage 3, urea formation. In this case, the amino group is transferred to oxaloacetate:

Specific example:



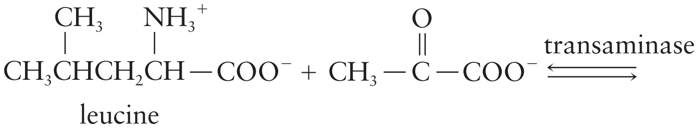
$$\underset{\text{valine}}{CH_3-\underset{\underset{CH_3}{|}}{CH}-\overset{NH_3^+}{\overset{|}{CH}}-COO^-} + \underset{\text{oxaloacetate}}{{}^-OOC-CH_2-\overset{O}{\overset{\|}{C}}-COO^-} \rightleftharpoons CH_3-\underset{\underset{CH_3}{|}}{CH}-\overset{O}{\overset{\|}{C}}-COO^- + \underset{\text{aspartate}}{{}^-OOC-CH_2-\overset{NH_3^+}{\overset{|}{CH}}-COO^-}$$

(24.12)

The net effect of the transamination reactions in the catabolism of amino acids is to use nitrogen from a variety of amino acids to form glutamate and aspartate. In **Section 24.11**, we'll see that transamination is also an important method in the biosynthesis of amino acids.

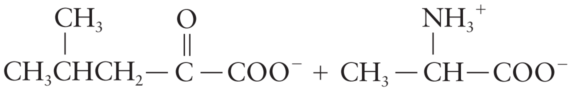
Example 24.4 Completing Transamination Reactions

Complete the following transamination reaction:



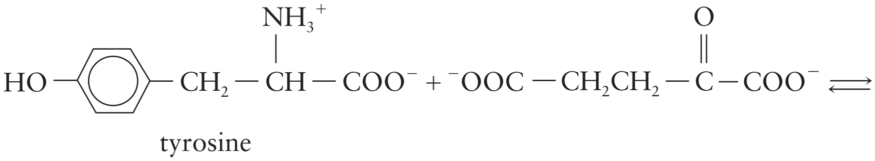
$$\underset{\text{leucine}}{CH_3\overset{CH_3}{\overset{|}{C}}HCH_2\overset{NH_3^+}{\overset{|}{CH}}-COO^-} + CH_3-\overset{O}{\overset{\|}{C}}-COO^- \xrightleftharpoons{\text{transaminase}}$$

Solution



$$CH_3\overset{CH_3}{\overset{|}{C}}HCH_2-\overset{O}{\overset{\|}{C}}-COO^- + CH_3-\overset{NH_3^+}{\overset{|}{CH}}-COO^-$$

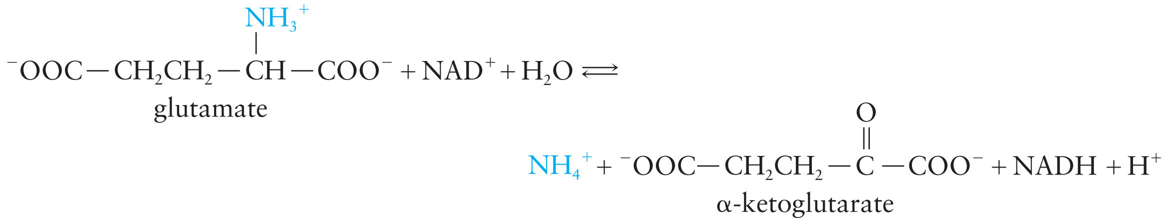
✔ **LEARNING CHECK 24.4** Complete the following transamination reaction:



24.9B Stage 2: Deamination

This phase of amino acid catabolism uses the glutamate produced in Stage 1. The enzyme glutamate dehydrogenase catalyzes the removal of the amino group as an ammonium ion and regenerates α-ketoglutarate, which can again participate in the first stage (transamination). This reaction is the principal source of NH_4^+ in humans. Because the deamination results in the oxidation of glutamate, it is called **oxidative deamination**:

oxidative deamination An oxidation process resulting in the removal of an amino group.



$$\underset{\text{glutamate}}{{}^-OOC-CH_2CH_2-\overset{NH_3^+}{\overset{|}{CH}}-COO^-} + NAD^+ + H_2O \rightleftharpoons NH_4^+ + \underset{\alpha\text{-ketoglutarate}}{{}^-OOC-CH_2CH_2-\overset{O}{\overset{\|}{C}}-COO^-} + NADH + H^+$$

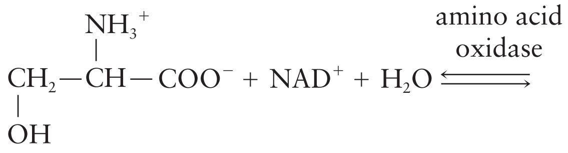
(24.13)

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

The NADH produced in this second stage enters the electron transport chain and eventually produces 2.5 ATP molecules. Other amino acids in addition to glutamate may also be catabolized by oxidative deamination. The reactions are catalyzed by enzymes in the liver called amino acid oxidases. In each case, an α-keto acid and NH_4^+ are the products.

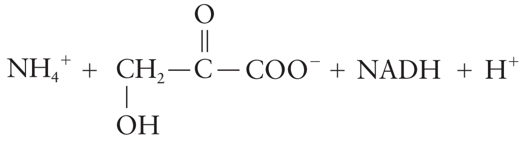
Example 24.5 Completing Deamination Reactions

Complete the following oxidative deamination reaction:



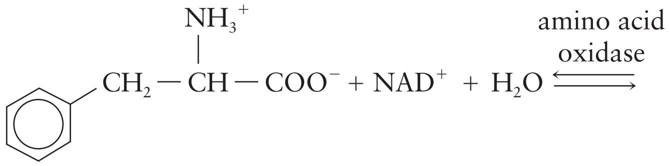
$$\underset{\displaystyle \mathrm{OH}}{\underset{|}{\mathrm{CH_2}}}-\overset{\displaystyle \mathrm{NH_3^+}}{\overset{|}{\mathrm{CH}}}-\mathrm{COO^-} + \mathrm{NAD^+} + \mathrm{H_2O} \overset{\text{amino acid oxidase}}{\rightleftharpoons}$$

Solution



$$\mathrm{NH_4^+} + \underset{\displaystyle \mathrm{OH}}{\underset{|}{\mathrm{CH_2}}}-\overset{\displaystyle \mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{COO^-} + \mathrm{NADH} + \mathrm{H^+}$$

✔ **LEARNING CHECK 24.5** Complete the following oxidative deamination reaction:

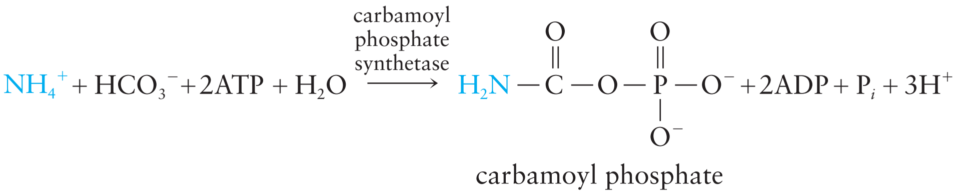


24.9C Stage 3: Urea Formation

The ammonium ions released by the glutamate dehydrogenase reaction are toxic to the body and must be prevented from accumulating. In the **urea cycle**, which occurs only in the liver, ammonium ions are converted to urea (see **Figure 24.13**). This compound is less toxic than ammonium ions and can be allowed to concentrate until it is convenient to excrete it in urine.

urea cycle A metabolic pathway in which ammonium ions are converted to urea.

The urea cycle processes the ammonium ions in the form of carbamoyl phosphate, the fuel for the urea cycle. This compound is synthesized in the mitochondria from ammonium ions and bicarbonate ions.



$$\mathrm{NH_4^+ + HCO_3^- + 2ATP + H_2O} \xrightarrow{\text{carbamoyl phosphate synthetase}} \mathrm{H_2N}-\overset{\displaystyle \mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{O}-\underset{\displaystyle \mathrm{O^-}}{\underset{|}{\overset{\displaystyle \mathrm{O}}{\overset{\|}{\mathrm{P}}}}}-\mathrm{O^-} + \mathrm{2ADP} + \mathrm{P}_i + \mathrm{3H^+} \tag{24.14}$$

carbamoyl phosphate

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

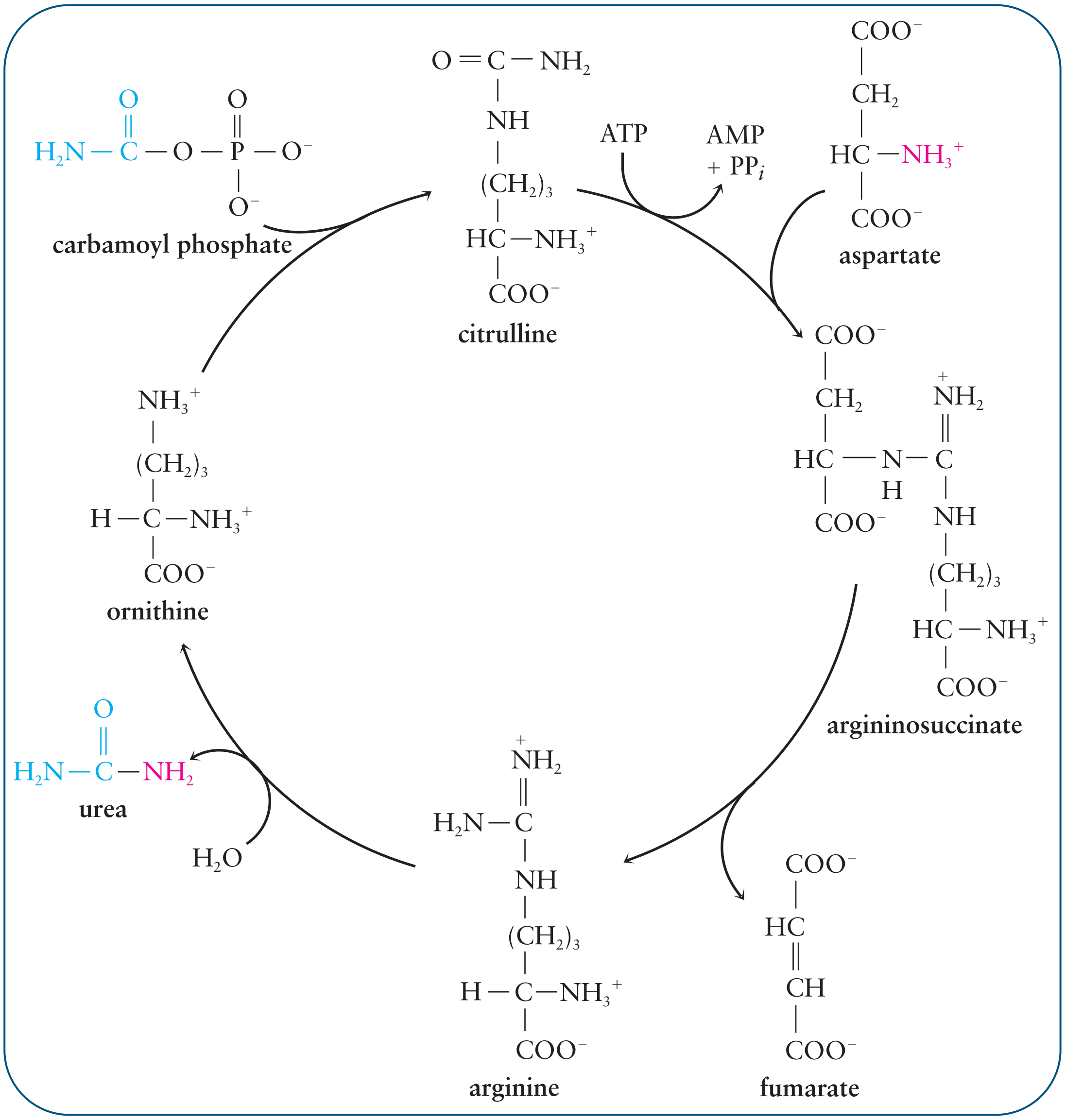
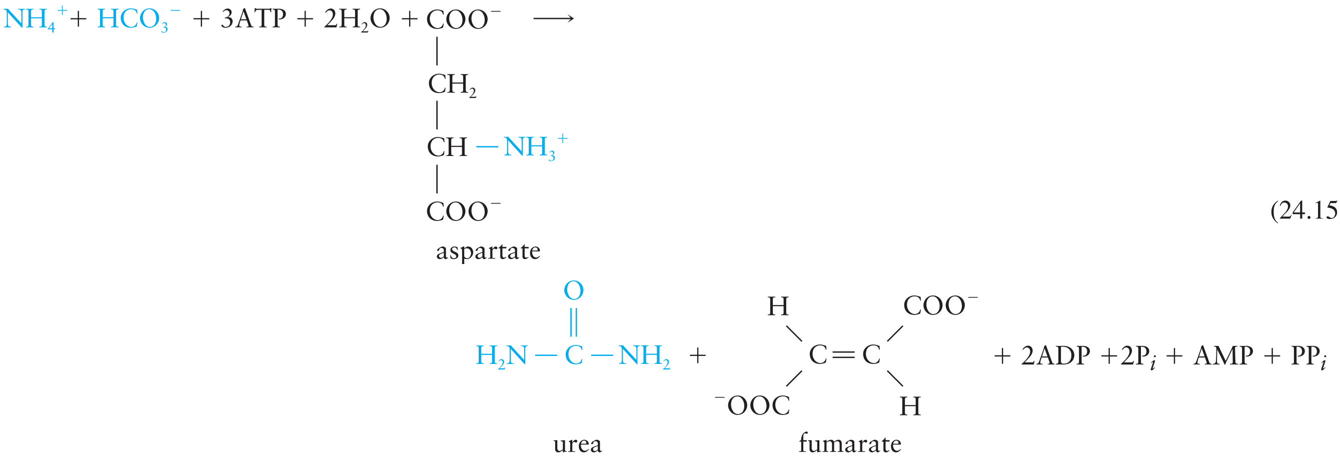


FIGURE 24.13 The urea cycle. Nitrogen atoms enter the cycle from carbamoyl phosphate and aspartate.

As we see, the energy for the synthesis of one molecule of carbamoyl phosphate is derived from two molecules of ATP. **Figure 24.13** summarizes the reactions of the urea cycle. The net reaction for carbamoyl phosphate formation and the urea cycle is



$$\mathrm{NH_4^+} + \mathrm{HCO_3^-} + 3\mathrm{ATP} + 2\mathrm{H_2O} + \underset{\text{aspartate}}{{}^-\mathrm{OOC{-}CH_2{-}CH(NH_3^+){-}COO^-}} \longrightarrow \underset{\text{urea}}{\mathrm{H_2N{-}C({=}O){-}NH_2}} + \underset{\text{fumarate}}{{}^-\mathrm{OOC{-}CH{=}CH{-}COO^-}} + 2\mathrm{ADP} + 2\mathrm{P}_i + \mathrm{AMP} + \mathrm{PP}_i \qquad (24.15)$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

After urea is formed, it diffuses out of liver cells into the blood, the kidneys filter it out, and it is excreted in the urine. Normal urine from an adult usually contains about 25 to 30 g of urea daily, although the exact amount varies with the protein content of the diet. The direct excretion of NH_4^+ accounts for a small but important amount of total urinary nitrogen. Ammonium ions can be excreted along with acidic ions, a mechanism that helps the kidneys control the acid–base balance of body fluids.

Example 24.6 Describing the Urea Cycle

a. Not counting phosphate compounds, name the two products of the urea cycle.
b. How many reactions comprise the urea cycle?
c. Once fuel enters the urea cycle, how much energy in terms of ATP is required for operation of the cycle?

Solution

a. Urea and fumarate
b. Four
c. 1 ATP

✔ LEARNING CHECK 24.6

a. What is the primary function of the urea cycle?
b. What is the fuel for the urea cycle?

24.10 Amino Acid Catabolism: The Fate of the Carbon Skeleton

Learning Objective 11 Describe how amino acids can be used for energy production, the synthesis of triglycerides, and gluconeogenesis.

After removal of the amino group of an amino acid is accomplished by transamination or oxidative deamination (see **Section 24.9**), the remaining carbon skeleton undergoes catabolism and is converted into one of several products. We will not study the various pathways followed, but we will focus on the final forms the skeleton assumes and the metabolic fate of these forms.

After the amino group is gone, the skeletons of all 20 amino acids are degraded into either pyruvate, acetyl CoA, acetoacetyl CoA (which is degraded to acetyl CoA), or various substances that are intermediates in the citric acid cycle. As shown in **Figure 24.14**,

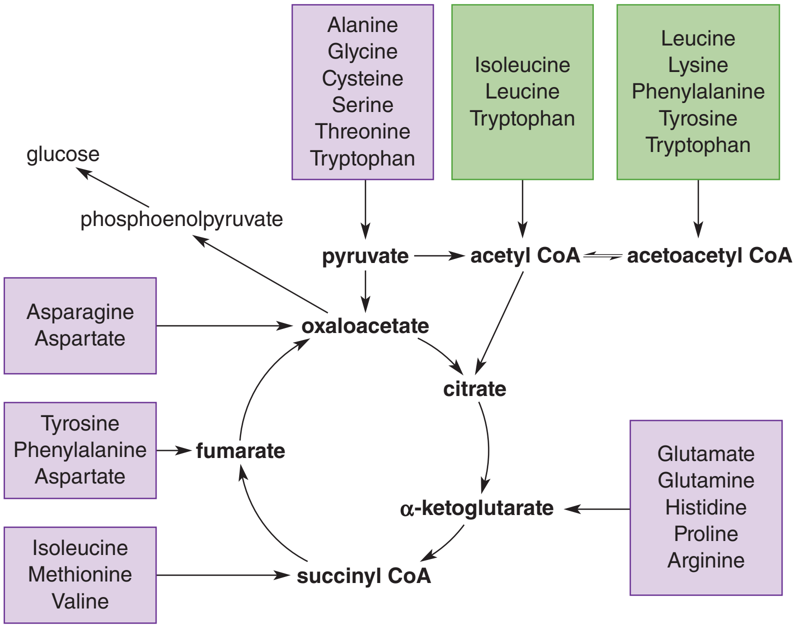

Alanine
Glycine
Cysteine
Serine
Threonine
Tryptophan
Isoleucine
Leucine
Tryptophan
Leucine
Lysine
Phenylalanine
Tyrosine
Tryptophan
glucose
phosphoenolpyruvate
pyruvate
acetyl CoA
acetoacetyl CoA
Asparagine
Aspartate
oxaloacetate
citrate
Tyrosine
Phenylalanine
Aspartate
fumarate
Glutamate
Glutamine
Histidine
Proline
Arginine
α-ketoglutarate
Isoleucine
Methionine
Valine
succinyl CoA

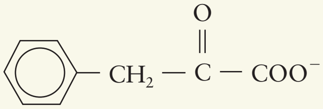
FIGURE 24.14 Fates of the carbon atoms of amino acids. Glucogenic amino acids are shaded purple, and ketogenic amino acids are shaded green.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

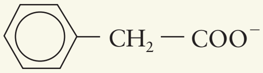
HEALTH CONNECTIONS **24.2**

Phenylketonuria (PKU)

At least 35 different hereditary changes in amino acid metabolism have been identified. One of the more well known is an inherited disease associated with abnormal aromatic amino acid metabolism. In *phenylketonuria (PKU),* there is a lack of the enzyme phenylalanine hydroxylase. As a result, phenylalanine cannot be converted to tyrosine, leading to the accumulation of phenylalanine and its metabolites (phenylpyruvate and phenylacetate) in the tissues and blood:



phenylpyruvate



phenylacetate

Abnormally high levels of phenylpyruvate and phenylacetate damage developing brain cells, causing severe mental retardation. It is estimated that 1 out of every 20,000 newborns is afflicted with PKU. A federal regulation requires that all infants be tested for this disease, which can be detected very easily by analyzing blood or urine samples for phenylalanine or phenylpyruvic acid.

The disease is treated by restricting the amount of phenylalanine in the diet of the infant starting 2 to 3 weeks after birth. The diet is also supplemented with tyrosine because it is not being formed in the PKU patient. Strict dietary management is not as critical after the age of 6 because the brain has matured by this time and is not as susceptible to the toxic effects of phenylalanine metabolites.

Mark Clarke/Science Source

Infants with PKU have an excellent chance for a normal healthy life, if the disease is detected and treated early. Here a nurse is taking blood samples from an infant's foot to be used in a simple chemical test for PKU.

all these degraded forms of the carbon skeletons are a part of or can enter the citric acid cycle, and thus may be very important in the production of energy.

Even though the degraded carbon skeletons can be used to produce energy via the citric acid cycle, not all are used this way because cellular needs might dictate other uses. For example, once a carbon skeleton is catabolized to pyruvate, there are two possible uses for it: the production of energy or the synthesis of glucose through gluconeogenesis (see **Section 23.10**). The skeleton of an amino acid that is degraded into pyruvate or intermediates of the citric acid cycle can be used to make glucose and is classified as a **glucogenic amino acid**. Amino acids with skeletons that are degraded into acetyl CoA or acetoacetyl CoA cannot be converted into glucose but can, in addition to energy production, be used to make ketone bodies and fatty acids. Such amino acids are classified as **ketogenic**. **Figure 24.14** shows this catabolic classification of the 20 amino acids. Notice that some amino acids appear in more than one location in the diagram.

glucogenic amino acid An amino acid whose carbon skeleton can be converted metabolically to an intermediate used in the synthesis of glucose.

ketogenic amino acid An amino acid whose carbon skeleton can be converted metabolically to acetyl CoA or acetoacetyl CoA.

Glucogenic amino acids play a special role in the metabolic changes that occur during starvation. To maintain the blood glucose level, the body first uses the glycogen stored in the liver. After 12 to 18 hours without food, the glycogen supplies are exhausted. Glucose is then synthesized from glucogenic amino acids through the process of gluconeogenesis. Hydrolysis of proteins from body tissues, particularly from muscle, supplies the amino acids for gluconeogenesis. Because each protein in the body has an important function, the body can meet its energy needs for only a limited time by sacrificing proteins.

HEALTH CONNECTIONS **24.3**

Phenylalanine and Diet Foods

In human society, we often want to indulge ourselves but we don't want to suffer any negative consequences of the indulgence. A good example of this is the desire to satisfy our craving for a sweet taste in foods, but not wanting to suffer the results of excessive caloric intake. As a result, a large industry has developed based on the production and distribution of low-calorie or no-calorie food sweeteners (see Health Connections 17.1). One popular product of this industry is a dipeptide of the two amino acids aspartic acid and phenylalanine. The product, called *aspartame,* has a sweet taste about 180 times that of ordinary table sugar (sucrose). When aspartame is hydrolyzed during digestion, the two amino acids are released.

Most foods that contain aspartame carry a warning on the label stating that they contain phenylalanine, although the phenylalanine is only released during the digestion of the food. The label warning is, for the most part, a protection for the food manufacturer against the somewhat remote possibility that the user of the food product suffers from a genetic metabolic disorder called phenylketonuria, or PKU (see Health Connections 24.2). The label warning also complies with federal regulations that require any food product containing aspartame to carry the warning.

People who have PKU suffer serious complications from ingesting phenylalanine, such as mental retardation, brain damage, seizures, and other problems. People who don't have PKU do not have to worry about ingesting phenylalanine or aspartame, with a certain few exceptions. It is known that aspartame or phenylalanine-rich foods can cause a rapid increase in brain levels of phenylalanine. So, aspartame and other products containing phenylalanine should be used cautiously by individuals with the following characteristics:

- Those who are taking medications such as monoamine oxidase inhibitors, neuroleptics, or medications containing levodopa
- Those who have a sleep disorder
- Those who have an anxiety disorder or other mental health disorder

John Crowe/Alamy Stock Photo

Aspartame is present in many low-calorie drinks.

Example 24.7 Describing Amino Acid Catabolism

a. How many amino acids are glucogenic?
b. How many amino acids are ketogenic?
c. How many amino acids are both glucogenic and ketogenic?

Solution

a. 18
b. 6
c. 4

✔ **LEARNING CHECK 24.7** What are the fates of carbon skeletons of

a. Glucogenic amino acids?
b. Ketogenic amino acids?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

24.11 Amino Acid Biosynthesis

Learning Objective 12 State the relationship between intermediates of carbohydrate metabolism and the synthesis of nonessential amino acids.

As we have already seen, the liver is highly active biochemically. In biosynthesis, it is responsible for producing most of the amino acids the body can synthesize. Amino acids that can be synthesized in the amounts needed by the body are called **nonessential amino acids** (see **Table 24.3**). As explained in **Chapter 22**, essential amino acids either cannot be made or cannot be made in large enough amounts to meet bodily needs and must be included in the diet (see **Figure 24.15**).

nonessential amino acid An amino acid that can be synthesized within the body in adequate amounts.

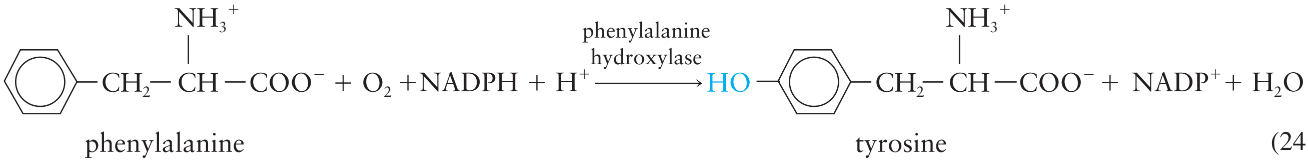
TABLE 24.3 Essential and Nonessential Amino Acids

Essential	Nonessential	Essential	Nonessential
Histidine	Alanine	Threonine	Glutamine
Isoleucine	Arginine	Tryptophan	Glycine
Leucine	Asparagine	Valine	Proline
Lysine	Aspartate		Serine
Methionine	Cysteine		Tyrosine
Phenylalanine	Glutamate		

DanaTentis/321 images/Pixabay

FIGURE 24.15 Good dietary sources of essential amino acids include meat, eggs, tofu, and dairy products.

The key starting materials for the synthesis of 10 nonessential amino acids are intermediates of the glycolysis pathway and the citric acid cycle (see **Figure 24.16**). Tyrosine, the only nonessential amino acid with an aromatic side chain, is produced from the essential amino acid phenylalanine in a conversion that requires a single oxidation step catalyzed by the enzyme phenylalanine hydroxylase:


NH3+
CH2 — CH — COO− + O2 + NADPH + H+
phenylalanine hydroxylase
HO
NH3+
CH2 — CH — COO− + NADP+ + H2O
phenylalanine
tyrosine

(24.16)

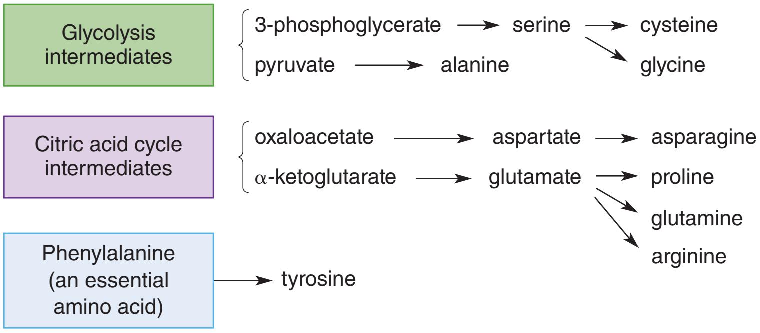
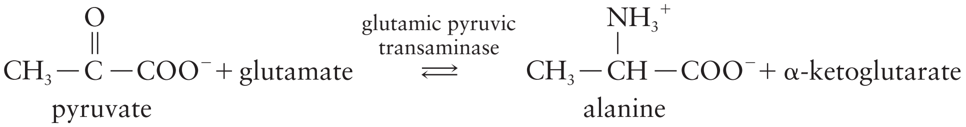

Glycolysis intermediates
3-phosphoglycerate
serine
cysteine
glycine
pyruvate
alanine
Citric acid cycle intermediates
oxaloacetate
aspartate
asparagine
α-ketoglutarate
glutamate
proline
glutamine
arginine
Phenylalanine (an essential amino acid)
tyrosine

FIGURE 24.16 A summary of amino acid biosynthesis.

Three nonessential amino acids (glutamate, alanine, and aspartate) are synthesized from α-keto acids via reactions catalyzed by transaminases. For example, alanine is produced from pyruvate and glutamate (which furnishes the amino group):



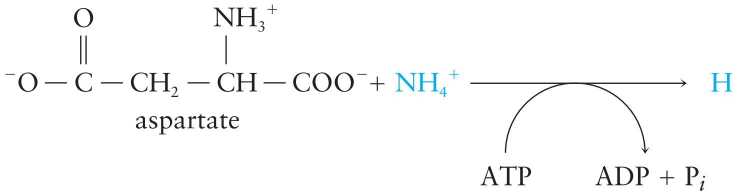
$$\underset{\text{pyruvate}}{CH_3-\overset{\displaystyle O}{\overset{\|}{C}}-COO^-} + \text{glutamate} \overset{\text{glutamic pyruvic transaminase}}{\rightleftharpoons} \underset{\text{alanine}}{CH_3-\overset{\displaystyle NH_3^+}{\overset{|}{CH}}-COO^-} + \alpha\text{-ketoglutarate}$$

(24.17)

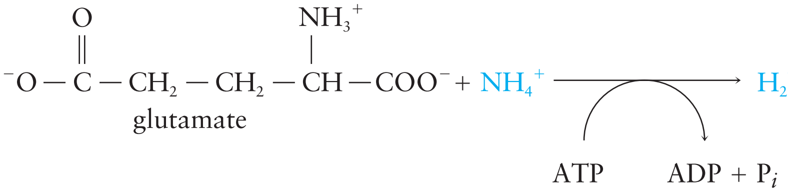
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Thus, we see that transaminases perform two vital functions in amino acid metabolism. By taking part in the biosynthesis of nonessential amino acids, they provide a means to help readjust the relative proportions of amino acids to meet the particular needs of the body. This is a vital function because most of our diets do not contain amino acids in the exact proportions the body requires. Also, as we noted in **Section 24.9**, transamination reactions allow the nitrogen atoms of all amino acids to be transferred to α-keto acids to form glutamate and aspartate when disposal of nitrogen is necessary.

Two other nonessential amino acids, asparagine and glutamine, are formed from aspartate and glutamate by reaction of the side-chain carboxylate groups with ammonium ions:



$$\underset{\text{aspartate}}{^{-}O-\overset{O}{\overset{\|}{C}}-CH_2-\overset{NH_3^+}{\overset{|}{CH}}-COO^-} + NH_4^+ \xrightarrow[\text{ATP} \quad \text{ADP} + P_i]{} \underset{\text{asparagine}}{H_2N-\overset{O}{\overset{\|}{C}}-CH_2-\overset{NH_3^+}{\overset{|}{CH}}-COO^-} \qquad (24.18)$$



$$\underset{\text{glutamate}}{^{-}O-\overset{O}{\overset{\|}{C}}-CH_2-CH_2-\overset{NH_3^+}{\overset{|}{CH}}-COO^-} + NH_4^+ \xrightarrow[\text{ATP} \quad \text{ADP} + P_i]{} \underset{\text{glutamine}}{H_2N-\overset{O}{\overset{\|}{C}}-CH_2CH_2-\overset{NH_3^+}{\overset{|}{CH}}-COO^-} \qquad (24.19)$$

So far, we have shown how 6 of the 11 nonessential amino acids are synthesized. The syntheses of the remaining 5 are more complex, and we will not consider them here.

Example 24.8 Describing Amino Acid Biosynthesis

How many amino acids may be synthesized from the following?

a. Phenylalanine
b. Intermediates of glycolysis
c. Intermediates of the citric acid cycle

Solution

a. 1
b. 4
c. 6

✔ **LEARNING CHECK 24.8** How many amino acids are

a. Essential?
b. Nonessential?

Health Career Description

PEDIATRIC NURSE

Proficiency in chemistry and biochemistry is of utmost importance to the pediatric nurse. As with any registered nurse, knowledge of medications, blood chemistry, ability to read lab results such as lipid panels and metabolic panels, and the ability to understand medication actions and interactions is critical. In the pediatric population, the margin of error is much smaller than in adults. Dosage errors of even a very small amount can have devastating effects, and medications can

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

affect children differently than adults. Therefore, specialized training beyond general registered nursing is required to become a pediatric nurse.

The need for pediatric nurses covers a wide spectrum from high-acuity children's hospitals to working in public health settings at schools or community clinics. Pediatric nurses may assist doctors, work shifts in a hospital, or conduct physicals at health fairs. Abundant possibilities exist for the pediatric nurse, and according to the Bureau of Labor Statistics, it is a career growing much faster than other careers in the United States.

Communication skills across a wide range of needs are vitally important for the pediatric nurse. Not only must the nurse be skilled in communicating with young children, from preverbal age to teenage children, but they must also navigate communication with concerned, often stressed, parents and other family members. Professional communication between colleagues and doctors adds to the list of situations the pediatric nurse must navigate seamlessly.

Pediatric nurses are called on not only to treat illness and provide care, but also to dispel fears and put a patient and family at ease. This requires a working knowledge of psychology and human behavior and significant adroitness in soft skills. Pediatric nurses are trained in special communication strategies to work specifically with children of different ages.

Because of specialized training beyond a 4-year bachelor's degree in nursing, pediatric nurses may expect to spend up to 6 years qualifying for a position. Pediatric nurses must have a bachelor's degree and meet state licensure requirements. Nurses may earn a certificate in pediatric nursing or may choose to pursue a master's degree in pediatric nursing practice.

Sources: ExploreHealthCareers.org. (n.d.). Pediatric Nurse. Retrieved July 18, 2020 from https://explorehealthcareers.org/career/nursing/pediatric-nurse/; Bureau of Labor Statistics, U.S. Department of Labor. Occupational Outlook Handbook, Registered Nurse. Retrieved July 18, 2020 from https://www.bls.gov/ooh/healthcare/registered-nurses.htm/

Concept Summary

24.1 Blood Lipids

Learning Objective: Can you describe the digestion, absorption, and distribution of lipids in the body?

- Fatty acids, glycerol, and monoglycerides that result from lipid digestion are absorbed into the lymph, recombined into triglycerides, and deposited into the bloodstream as lipoprotein aggregates.

24.2 Fat Mobilization

Learning Objective: Can you explain what happens during fat mobilization?

- When stored fats are needed for energy, hydrolysis reactions liberate the fatty acids and glycerol.
- These component substances of fat then enter the bloodstream and travel to tissues, where they are utilized.

24.3 Glycerol Metabolism

Learning Objective: Can you identify the metabolic pathway by which glycerol is catabolized?

- The glycerol available from fat mobilization is first phosphorylated and then oxidized to dihydroxyacetone phosphate, an intermediate of glycolysis.
- By having an entry point into the glycolysis pathway, glycerol can ultimately be converted into glucose or oxidized to CO_2 and H_2O.

24.4 The Oxidation of Fatty Acids

Learning Objective: Can you outline the steps of β-oxidation for fatty acids?

- The catabolism of fatty acids begins in the cytoplasm, where they are activated by combining with CoA–SH.
- After being transported into mitochondria, the degradation of fatty acids occurs by the β-oxidation pathway.
- The β-oxidation pathway produces reduced coenzymes ($FADH_2$ and NADH) and cleaves the fatty acid chain into two-carbon fragments bound to coenzyme A (acetyl CoA).

24.5 The Energy from Fatty Acids

Learning Objective: Can you determine the amount of ATP produced by the complete catabolism of a fatty acid?

- The energy available from a fatty acid for ATP synthesis can be calculated by determining the amount of acetyl CoA, $FADH_2$, and NADH produced.
- On an equal-mass basis, fatty acids contain more than twice the energy of glucose.

24.6 Ketone Bodies

Learning Objective: Can you name the three ketone bodies and list the conditions that cause their overproduction?

- Acetoacetate, β-hydroxybutyrate, and acetone are known as ketone bodies.
- They are synthesized in the liver from acetyl CoA.
- During starvation, in unchecked diabetes, and after excessive alcohol consumption, the level of ketone bodies becomes very high, leading to several conditions.
- These conditions are: ketonemia, ketonuria, acetone breath, and ketosis.

24.7 Fatty Acid Synthesis

Learning Objective: Can you describe the pathway for fatty acid synthesis?

- This process occurs in the cytoplasm and uses acetyl CoA as a starting material.
- Two-carbon fragments are added to growing fatty acid molecules as energy is supplied by ATP and NADPH.

24.8 Amino Acid Metabolism

Learning Objective: Can you describe the source and function of the body's amino acid pool?

- Amino acids and proteins are not stored within the body.
- Amino acids absorbed from digested food or synthesized in the body become part of a temporary supply or pool that may be used in metabolic processes.
- The turnover, or life expectancy, of proteins is usually expressed in half-lives.
- Protein half-lives range from several minutes to hundreds of days.
- Some amino acids in the body are converted into relatively simple but vital nitrogen-containing compounds.
- The catabolism of amino acids produces intermediates used for energy production, synthesis of glucose, or formation of triglycerides.

24.9 Amino Acid Catabolism: The Fate of the Nitrogen Atoms

Learning Objective: Can you write equations for transamination and deamination reactions? Can you explain the overall results of the urea cycle?

- As an amino acid undergoes catabolism, the amino group may be transferred to an α-keto acid through a process called transamination.
- In the process of deamination, an amino acid is converted into a keto acid and ammonia.
- The urea cycle converts toxic ammonium ions into urea for excretion.

24.10 Amino Acid Catabolism: The Fate of the Carbon Skeleton

Learning Objective: Can you describe how amino acids can be used for energy production, the synthesis of triglycerides, and gluconeogenesis?

- Amino acids are classified as glucogenic or ketogenic based on their catabolic products.
- Glucogenic amino acids are degraded into pyruvate or intermediates of the citric acid cycle and can be used for glucose synthesis.
- Ketogenic amino acids are degraded into acetoacetyl CoA and acetyl CoA for energy production and triglyceride synthesis.

24.11 Amino Acid Biosynthesis

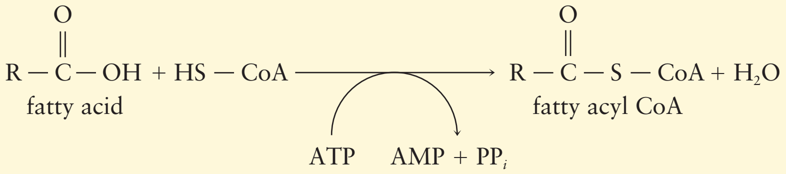
Learning Objective: Can you state the relationship between intermediates of carbohydrate metabolism and the synthesis of nonessential amino acids?

- The body can synthesize amino acids, known as nonessential amino acids.
- The key starting materials are intermediates of the glycolysis pathway and the citric acid cycle and, in the case of tyrosine, phenylalanine.

Key Terms and Concepts

Acetone breath (24.6)
Acidosis (24.6)
Adipose tissue (24.2)
Amino acid pool (24.8)
β-oxidation process (24.4)
Chylomicron (24.1)
Fat mobilization (24.2)
Glucogenic amino acid (24.10)
Ketoacidosis (24.6)
Ketogenic amino acid (24.10)
Ketone bodies (24.6)
Ketonemia (24.6)
Ketonuria (24.6)
Ketosis (24.6)
Nonessential amino acid (24.11)
Oxidative deamination (24.9)
Protein turnover (24.8)
Transaminase (24.9)
Transamination (24.9)
Urea cycle (24.9)

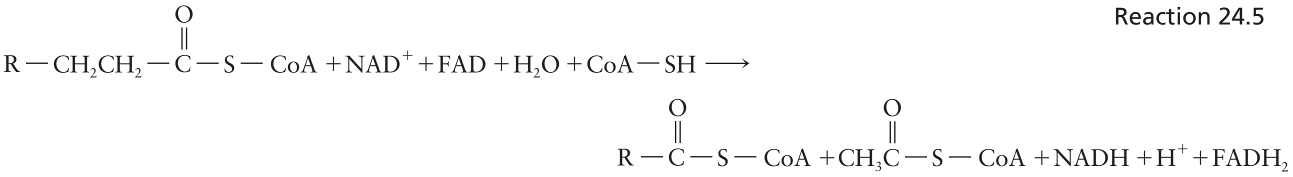
Key Equations

1. Digestion of triglycerides (**Section 24.1**):	$\text{triglyceride} + H_2O \xrightarrow{\text{lipase}} \text{fatty acids} + \text{glycerol} + \text{monoglycerides}$	
2. Fat mobilization (**Section 24.2**):	$\text{triglyceride} + 3H_2O \xrightarrow{\text{lipase}} 3\ \text{fatty acids} + \text{glycerol}$	
3. Activation of fatty acids (**Section 24.4**):	 $\underset{\text{fatty acid}}{\mathrm{R-\overset{O}{\overset{\parallel}{C}}-OH}} + \mathrm{HS-CoA} \xrightarrow[\text{ATP} \quad \text{AMP} + \text{PP}_i]{} \underset{\text{fatty acyl CoA}}{\mathrm{R-\overset{O}{\overset{\parallel}{C}}-S-CoA}} + H_2O$	Reaction 24.2

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

4. Oxidation of fatty acids (**Section 24.4**):

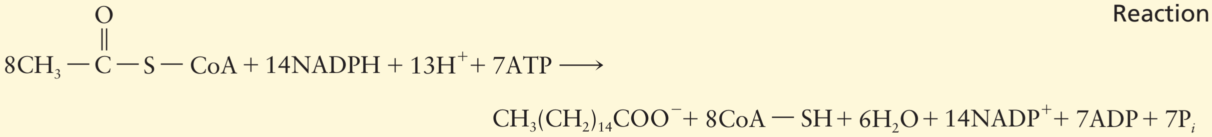
Reaction 24.5



$$R-CH_2CH_2-\overset{O}{\overset{\|}{C}}-S-CoA + NAD^+ + FAD + H_2O + CoA-SH \longrightarrow R-\overset{O}{\overset{\|}{C}}-S-CoA + CH_3\overset{O}{\overset{\|}{C}}-S-CoA + NADH + H^+ + FADH_2$$

5. Fatty acid synthesis (**Section 24.7**):

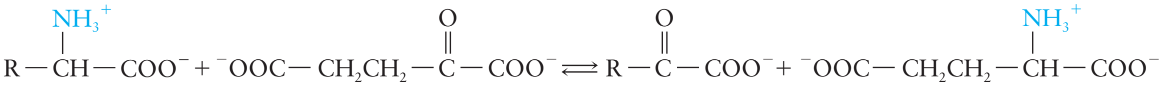
Reaction 24.9



$$8CH_3-\overset{O}{\overset{\|}{C}}-S-CoA + 14NADPH + 13H^+ + 7ATP \longrightarrow CH_3(CH_2)_{14}COO^- + 8CoA-SH + 6H_2O + 14NADP^+ + 7ADP + 7P_i$$

6. Transamination (**Section 24.9**):

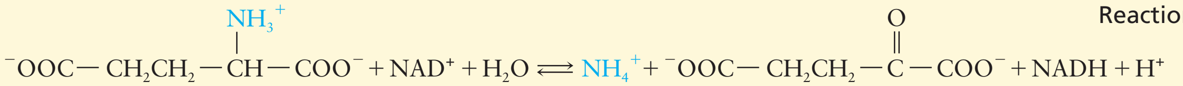
Reaction 24.10



$$R-\overset{NH_3^+}{\overset{|}{CH}}-COO^- + {}^-OOC-CH_2CH_2-\overset{O}{\overset{\|}{C}}-COO^- \rightleftharpoons R-\overset{O}{\overset{\|}{C}}-COO^- + {}^-OOC-CH_2CH_2-\overset{NH_3^+}{\overset{|}{CH}}-COO^-$$

7. Oxidative deamination (**Section 24.9**):

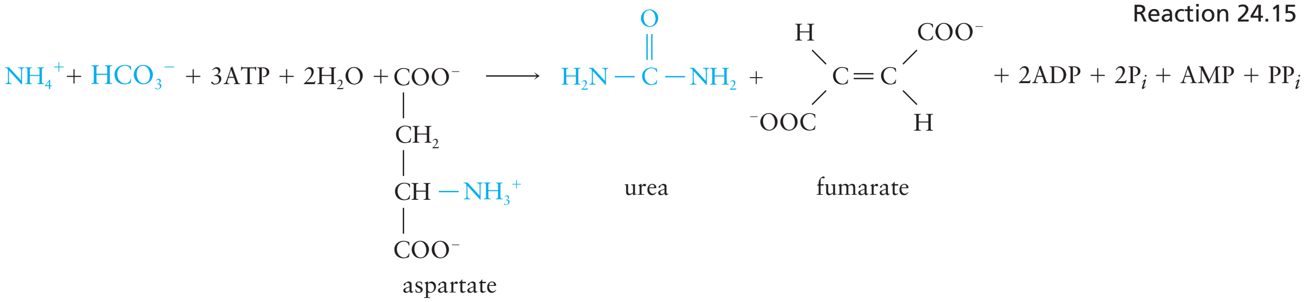
Reaction 24.13



$$^-OOC-CH_2CH_2-\overset{NH_3^+}{\overset{|}{CH}}-COO^- + NAD^+ + H_2O \rightleftharpoons NH_4^+ + {}^-OOC-CH_2CH_2-\overset{O}{\overset{\|}{C}}-COO^- + NADH + H^+$$

8. Urea formation (**Section 24.9**):

Reaction 24.15



Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

Blood Lipids (Section 24.1)

24.1 How does the caloric value of fat compare with the caloric value of glycogen and starch?

24.2 What are the products of triglyceride digestion?

24.3 What happens to the products of triglyceride digestion as they pass into the cells of the intestinal mucosa?

24.4 What mechanism exists in the body for transporting insoluble lipids?

24.5 What is a chylomicron, and what is its function?

24.6 Describe what happens to the level of blood lipids after a meal rich in fat.

24.7 List the major types of lipoproteins.

24.8 Which class of lipoproteins has the greatest amount of cholesterol?

24.9 Arrange the four classes of lipoproteins in order of increasing amounts of triglycerides.

24.10 Arrange the four classes of lipoproteins in order of increasing amounts of protein.

Fat Mobilization (Section 24.2)

24.11 Describe the relationship between epinephrine and fat mobilization.

24.12 Describe what is meant by the term *fat mobilization.*

24.13 Explain why red blood cells can't oxidize fatty acids.

24.14 Describe the function of adipose tissue.

24.15 What blood protein is important in fat mobilization?

24.16 Explain why fatty acids cannot serve as fuel for the brain.

24.17 Which cells utilize fatty acids over glucose to satisfy their energy needs?

Glycerol Metabolism (Section 24.3)

24.18 At what point does glycerol enter the glycolysis pathway?

24.19 In what cellular location is glycerol converted to dihydroxy acetone phosphate?

24.20 How many molecules of ATP are needed for the conversion of glycerol to an intermediate of glycolysis?

24.21 How many reactions are involved in the conversion of glycerol to an intermediate of glycolysis?

24.22 Describe the two fates of glycerol after it has been converted to an intermediate of glycolysis.

The Oxidation of Fatty Acids (Section 24.4)

24.23 Where in the cell does fatty acid catabolism take place?

24.24 How is the fatty acid prepared for catabolism? Where in the cell does fatty acid activation take place?

24.25 Acyl CoA synthetase activates a fatty acid by converting it to a high-energy thioester. Identify the thioester.

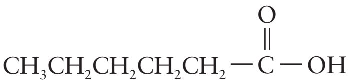
24.26 How many high-energy bonds in ATP are used to activate a fatty acid?

24.27 Why is the oxidation of fatty acids referred to as β-oxidation?

24.28 What hydrogen-transporting coenzymes play important roles in the oxidation of fatty acids?

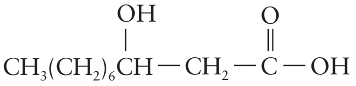
24.29 Label the α- and β-positions in the following acids:

a.



$\mathrm{CH_3CH_2CH_2CH_2CH_2-\overset{\overset{O}{\|}}{C}-OH}$

b.



$\mathrm{CH_3(CH_2)_6\overset{\overset{OH}{|}}{C}H-CH_2-\overset{\overset{O}{\|}}{C}-OH}$

24.30 Write an equation for the activation of palmitic acid (16 carbons).

24.31 Write formulas for the products that result when activated palmitic acid is taken through the following:

a. One turn of the fatty acid spiral

b. Two turns of the fatty acid spiral

24.32 Why is the oxidation of fatty acids referred to as the fatty acid spiral rather than the fatty acid cycle?

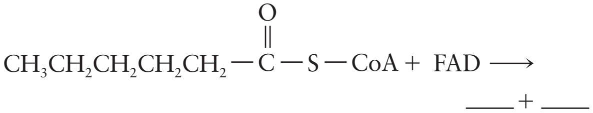
24.33* How many molecules of acetyl CoA are produced in the catabolism of a molecule of stearic acid, an 18-carbon carboxylic acid? How many times does the spiral reaction sequence occur?

24.34 How many turns of the fatty acid spiral are required to break down tetracosanoic acid, a 24-carbon fatty acid?

24.35 How many molecules of acetyl CoA, $FADH_2$, and NADH are produced by the complete β-oxidation of tetracosanoic acid?

24.36 Complete the following equations for one turn of the fatty acid spiral:

a.



$\mathrm{CH_3CH_2CH_2CH_2CH_2-\overset{\overset{O}{\|}}{C}-S-CoA + FAD \longrightarrow}$ ____ + ____

b. _____ + $H_2O \rightarrow$ _____

c. _____ + $NAD^+ \rightarrow$ ___ + ___ + ___

d. _____ + CoA—SH $\rightarrow$ ___ + ___

24.37 Outline the four reactions that occur in the fatty acid spiral.

The Energy from Fatty Acids (Section 24.5)

24.38 Determine the ATP yield per molecule of acetyl CoA that enters the citric acid cycle.

24.39 What is the energy cost in ATP molecules to activate a fatty acid?

24.40 On the basis of equal number of carbon atoms, how much more efficient are lipids than sugars as an energy source?

24.41 On an equal mass basis, how much more efficient are lipids than sugars as an energy source?

24.42* Calculate the number of ATP molecules that can be produced from the complete oxidation of a 10-carbon fatty acid to carbon dioxide and water.

24.43 Compare the energy available (in ATP molecules) from a six-carbon fatty acid to the energy available from a molecule of glucose.

Ketone Bodies (Section 24.6)

24.44 List the three substances known as ketone bodies.

24.45 Explain how excessive ketone bodies may form in the following:

a. During starvation

b. In patients with diabetes mellitus

24.46 Where are ketone bodies formed? What tissues utilize ketone bodies to meet energy needs?

24.47 Why does acetyl CoA build up in a low-carbohydrate diet?

24.48 Explain how ketoacidosis can result in dehydration.

24.49 Which ketone body has the highest blood level during starvation?

24.50 Why is sodium bicarbonate sometimes given to patients experiencing ketoacidosis?

24.51 Differentiate between (a) ketonemia, (b) ketonuria, (c) acetone breath, and (d) ketosis.

24.52 Why is ketosis frequently accompanied by acidosis?

Fatty Acid Synthesis (Section 24.7)

24.53 Where within a liver cell does fatty acid synthesis occur?

24.54 What substance supplies the carbons for fatty acid synthesis?

24.55 What substances furnish the energy for fatty acid synthesis?

24.56 How does citrate move from the mitochondria to the cytoplasm?

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

24.57 How many enzymes and other proteins are found in the fatty acid synthetase system?

24.58 What does the designation ACP stand for?

24.59 How many total ATP equivalents are needed for the synthesis of palmitate if each NADPH can generate 2.5 ATPs?

24.60 Which fatty acids are considered essential to the diet? Explain why.

24.61 Why can the liver convert glucose to fatty acids but cannot convert fatty acids to glucose?

Amino Acid Metabolism (Section 24.8)

24.62 List three vital functions served by amino acids in the body.

24.63 What name is given to the cellular supply of amino acids?

24.64 What are the sources of amino acids in the pool?

24.65 What term is used to denote the breakdown and resynthesis of body proteins?

24.66 What percentage of amino acids is used to synthesize proteins?

24.67 What happens to the nitrogen atoms in degraded amino acids?

24.68 Name four important biomolecules other than proteins that are synthesized from amino acids.

24.69 Compare the half-life of plasma proteins with the half-life of enzymes.

Amino Acid Catabolism: The Fate of the Nitrogen Atoms (Section 24.9)

24.70 Match the terms *transamination* and *deamination* to the following:

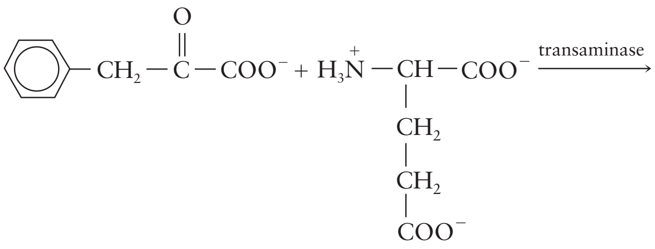
a. An amino group is removed from an amino acid and donated to a keto acid.

b. An ammonium ion is produced.

c. New amino acids are synthesized from other amino acids.

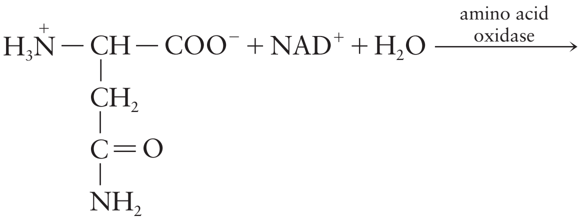
d. A keto acid is produced from an amino acid.

24.71* Complete the following transamination reaction and name the amino acid that is produced:



24.72 Write an equation to illustrate transamination between leucine and pyruvate.

24.73* Complete the following oxidative deamination reaction:



$$H_3\overset{+}{N}-\underset{\substack{|\\ CH_2\\ |\\ C=O\\ |\\ NH_2}}{CH}-COO^- + NAD^+ + H_2O \xrightarrow[\text{oxidase}]{\text{amino acid}}$$

24.74 Write an equation to illustrate the oxidative deamination of glycine.

24.75* By writing two reactions, the first a transamination and the second an oxidative deamination, show how the amino group of alanine can be removed as NH_4^+.

24.76 In what organ of the body is urea synthesized?

24.77 What are the sources of the carbon atom and two nitrogen atoms in urea?

24.78 Name the compound that enters the urea cycle by combining with ornithine.

24.79 How much energy (in number of ATP molecules) is expended to synthesize a molecule of urea?

24.80 Write a summary equation of the formation of urea.

Amino Acid Catabolism: The Fate of the Carbon Skeleton (Section 24.10)

24.81 Differentiate between glucogenic and ketogenic amino acids.

24.82 Is any amino acid both glucogenic and ketogenic?

24.83 Identify the five locations at which the carbon skeletons of amino acids enter the citric acid cycle.

24.84 What enzyme is responsible for PKU?

24.85 Based on the following conversions, classify each amino acid as glucogenic or ketogenic.

a. aspartate → oxaloacetate

b. leucine → acetyl CoA

c. tyrosine → acetoacetyl CoA

24.86 What special role is played by glucogenic amino acids during fasting or starvation?

Amino Acid Biosynthesis (Section 24.11)

24.87 Differentiate between essential and nonessential amino acids.

24.88 What essential amino acid makes tyrosine nonessential?

24.89 Where do the starting materials for nonessential amino acids come from?

24.90 What type of reaction is the phenylalanine-to-tyrosine conversion?

24.91 Pyruvate and glutamate are converted to alanine and α-ketoglutarate. What metabolic pathway contains α-ketoglutarate?

24.92 List two vital functions performed by transaminases.

24.93 What amino acids are synthesized from glutamate?

24.94 List two general sources of intermediates for the biosynthesis of amino acids.

Additional Exercises

24.95 Trace glycerol metabolism after it enters the glycolytic pathway as dihydroxyacetone phosphate and give an overall net reaction (including ATP, NAD^+, etc.) for the conversion of glycerol to pyruvate.

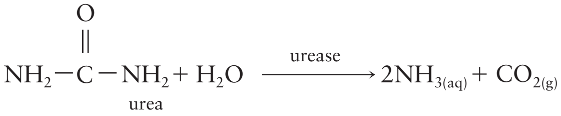
24.96 A change in the concentration of enzymes that catalyze fatty acid synthesis has been shown to be a major mechanism for controlling synthesis rate. Give two regulatory means of changing enzyme concentrations.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

24.97 A ketone body has a molecular weight of 58.1 g/mol and a concentration of 0.050 mg/100 mL in a patient's blood. Which ketone body is it, and how many molecules of it would be found in 1.0 mL of the patient's blood?

24.98 A 7.48-mg sample of a blood lipid was found to contain 1.87 mg of protein. Use **Figure 24.5** to classify this lipid.

24.99 The following reaction proceeded in an aqueous solution as the pH was monitored. After a while, the pH quit changing even though there was excess urea present in the solution.



$$\underbrace{NH_2-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2}_{\text{urea}} + H_2O \xrightarrow{\text{urease}} 2NH_{3(aq)} + CO_{2(g)}$$

Was the initial pH when the reaction began acidic, neutral, or basic? How did the pH change over time? Why did the pH quit changing?

Chemistry for Thought

24.100 Cellular reactions for the biosynthesis and catabolism of amino acids are not simply the reversals of the same metabolic pathways. Why is this an advantage for the cell?

24.101 Why do you think the half-lives of enzymes are comparatively short?

24.102 Why do you think the half-life of collagen is comparatively long?

24.103 How might HDL levels suggest a partial explanation for the observation that women as a group have fewer heart attacks than do men as a group?

24.104 A student calculates the net yield of ATP molecules from a 12-carbon fatty acid to be 80. What did the student probably overlook?

24.105 If researchers discovered a method of reducing blood cholesterol to extremely low levels, why might it be undesirable to do so?

24.106 Could there be a connection between high sugar intake and high blood levels of triglycerides? Explain.

25 Body Fluids

BSIP/Newscom

Health Career Focus

PERFUSIONIST

I'm naturally confident—and you need confidence to do this job. As a perfusionist working at a metropolitan hospital, I literally have the patient's life in my hands.

When a patient presents for cardiac surgery, the cardiologist can't work on a beating heart, so we hook the patient up to an Extracorporeal Membrane Oxygenation (ECMO) machine. That stands for extracorporeal membrane oxygenation—an out-of-body artificial lung machine. By running the patient's blood through this machine, we're able to stop the heart for the duration of the surgery.

It's my responsibility to make sure all the numbers are correct. I watch the temperature, oxygen and CO_2 levels, and even administer medications through the machine. I'm in charge of life support during surgery. Sometimes, ECMO is used when pneumonia or trauma patients need a rest from breathing on their own. I help with that as well.

It takes a certain type of person to want to do this. I'm not sure where I got my confidence, but I'm well suited to this demanding job.

Follow-up to this Career Focus appears at the end of the chapter before the *Concept Summary*.

Learning Objectives

When you have completed your study of this chapter, you should be able to:

1. Compare the chemical compositions of plasma, interstitial fluid, and intracellular fluid. **(Section 25.1)**
2. Explain how oxygen and carbon dioxide are transported within the bloodstream. **(Section 25.2)**
3. Explain how materials move from the blood into the body cells and from the body cells into the blood. **(Section 25.3)**
4. List the normal and abnormal constituents of urine. **(Section 25.4)**
5. Discuss how proper fluid and electrolyte balance is maintained in the body. **(Section 25.5)**
6. Explain how acid–base balance is maintained in the body. **(Section 25.6)**
7. Explain how buffers work to control blood pH. **(Section 25.7)**
8. Describe respiratory control of blood pH. **(Section 25.8)**
9. Describe urinary control of blood pH. **(Section 25.9)**
10. List the causes of acidosis and alkalosis. **(Section 25.10)**

TO CARRY OUT ITS COMPLEX FUNCTIONS, a living cell requires a steady supply of reactants, such as nutrients and oxygen. A cell also requires a reliable system for removing the resulting waste products—for example, carbon dioxide and water. Both of these conditions are met by the simple process of diffusion. Reactants can diffuse into the cell through the thin cell membrane, and the products of cell function can diffuse out of the cell and be absorbed by the surrounding liquid.

However, a complex organism, which consists of many closely packed cells, cannot depend solely on diffusion. Some circulating system must bring necessary materials to the cells and carry away the wastes. Otherwise, the liquid surrounding the cells would soon be depleted of reactants and saturated with wastes.

25.1 A Comparison of Body Fluids

Learning Objective 1 Compare the chemical compositions of plasma, interstitial fluid, and intracellular fluid.

The average adult body contains about 42 L of fluids, which accounts for two-thirds of the total body weight. Most of these fluids are compartmentalized in three regions of the body: the interior of cells, tissue spaces between cells (including the lymph vessels), and the blood vessels. The majority, about 28 L, is located inside the cells and is called **intracellular fluid**. All body fluids not located inside the cells are collectively known as **extracellular fluids**. Thus, fluids in two of the fluid compartments are extracellular: the **interstitial fluid**, which fills the space between tissue cells and moves in lymph vessels, and the fluid of the bloodstream—**plasma**. Interstitial fluid constitutes about 25% (10.5 L) of the total body fluid, and the plasma (nearly 3.5 L) makes up about 8% of the total. Other body fluids that occur in lesser amounts are urine, digestive juices, and cerebrospinal fluid. The distribution of the various body fluids is illustrated in **Figure 25.1**. Extracellular fluid provides a relatively constant environment for the cells and transports substances to and from the cells. Intracellular fluid, on the other hand, is the medium in which the vital life-maintaining reactions take place.

intracellular fluid Body fluid located inside cells.

extracellular fluid Body fluid located outside cells.

interstitial fluid The fluid surrounding individual tissue cells.

plasma The liquid portion of whole blood.

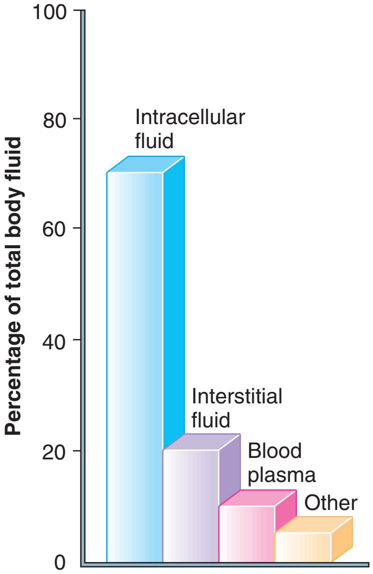
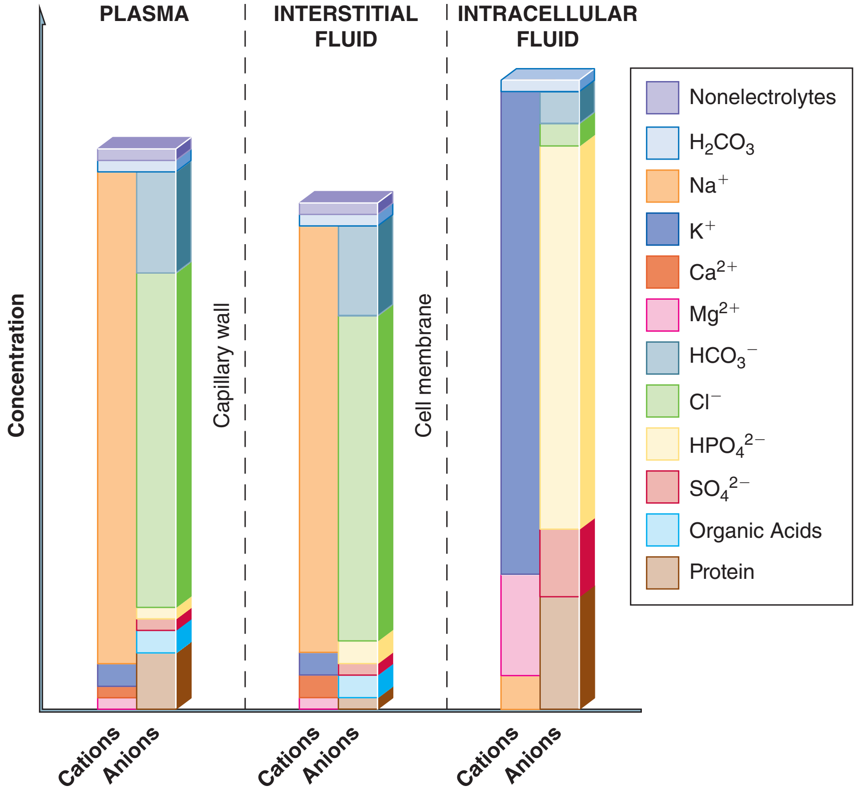


FIGURE 25.1 The distribution of body fluids.

Chemically, the two extracellular fluids, plasma and interstitial fluid, are nearly identical. The only difference is that plasma contains an appreciable amount of protein not found in interstitial fluid. Intracellular fluid is chemically different from extracellular fluid. Intracellular fluid contains larger amounts of protein and a much different ionic population (see **Figure 25.2**). From **Figure 25.2**, we can see that:

1. The principal cation of plasma and interstitial fluid is Na^+. The principal cation of intracellular fluid is K^+ (actually, about 98% of the body's potassium is found inside cells).
2. The principal anion of extracellular fluid is chloride, Cl^-, whereas phosphate (mainly HPO_4^{2-}) is the main anion inside cells.
3. Intracellular fluid contains more than four times as much protein as plasma, and there is remarkably little protein in interstitial fluid.

FIGURE 25.2 The relative chemical composition of the major body fluids.



Example 25.1 Comparing Body Fluids

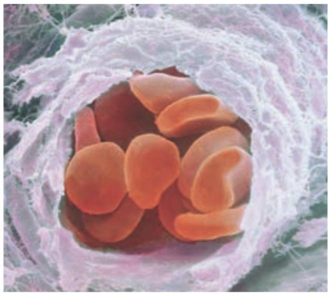
a. Which body fluid is present in greatest amounts?
b. What cation predominates in blood plasma?
c. What cation predominates in intracellular fluid?

Solution

a. Intracellular fluid
b. Na^+
c. K^+

✔ LEARNING CHECK 25.1

a. What cation predominates in interstitial fluid?
b. What anion predominates in interstitial fluid?
c. What anion predominates in intracellular fluid?



Professors Pietro M. Motta & Silvia Correr/ Science Source

FIGURE 25.3 Red blood cells passing through a narrow capillary.

oxyhemoglobin Hemoglobin combined with oxygen.

deoxyhemoglobin (hemoglobin) Nonoxygenated hemoglobin.

25.2 Oxygen and Carbon Dioxide Transport

Learning Objective 2 Explain how oxygen and carbon dioxide are transported within the bloodstream.

One of the most important functions of blood is to carry oxygen from the lungs to the tissues. An average adult at rest requires about 350 mL of oxygen per minute. The limited solubility of oxygen in plasma allows only about 2% of this total to be dissolved and transported in solution. About 98% of the needed oxygen is carried by red blood cells (see **Figure 25.3**) in the form of an oxygen-hemoglobin combination called **oxyhemoglobin**. The nonoxygenated hemoglobin is called **deoxyhemoglobin**, or simply **hemoglobin**. Normal human blood contains about 15 g of hemoglobin per 100 mL.

Because of its physiological importance, hemoglobin has been studied extensively. It is known to be a conjugated protein containing four chains (the globin portion of

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

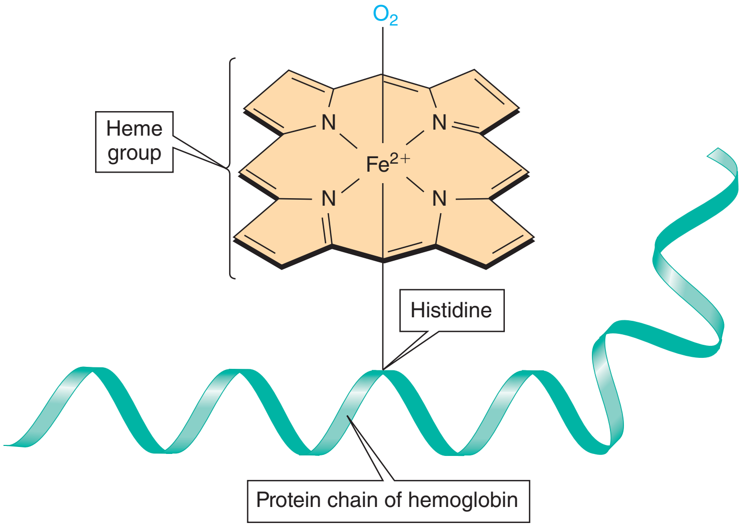


FIGURE 25.4 The iron in oxyhemoglobin.

the molecule) and four heme groups. Each heme group consists of an Fe^{2+} ion in the center of a nitrogenous heterocyclic structure (see **Figure 25.4**). The iron in oxyhemoglobin is bonded at six positions, as shown in **Figure 25.4**. The four nitrogens are part of the heme group, and the iron is directly attached to the histidine, which is a part of the globin molecule. The sixth bond is between iron and oxygen. Because each hemoglobin molecule contains four heme groups, it can bind a total of four O_2 molecules. When one of the four heme groups binds an oxygen molecule, the affinity of the other heme groups for oxygen is increased. The reversible binding that takes place between hemoglobin (Hb) and molecular oxygen is represented like this:

$$\underset{\text{hemoglobin}}{HHb} + O_2 \rightleftharpoons \underset{\text{oxyhemoglobin}}{HbO_2^-} + H^+ \qquad (25.1)$$

carbaminohemoglobin Hemoglobin combined with carbon dioxide.

When CO_2 is present, hemoglobin can combine with it to form **carbaminohemoglobin**. This reversible reaction is favored by conditions found in body tissues:

$$HHb + CO_2 \rightleftharpoons \underset{\text{carbaminohemoglobin}}{HHbCO_2} \qquad (25.2)$$

About 25% of the total CO_2 in the body is carried from body tissues to the lungs in the form of carbaminohemoglobin. Another 5% dissolves in the plasma and travels in solution; the remaining 70% is transported in the form of bicarbonate ions (HCO_3^-).

The transport of oxygen to tissues begins when inhaled air (see **Figure 25.5**) fills the alveoli of the lungs. These clusters of small sacs are surrounded by many tiny blood capillaries, and it is here that oxygen is absorbed into the blood. **Figure 25.6** represents the processes that take place as oxygen is absorbed and carbon dioxide is released. The main steps (circled numbers in the figure) are:

1. Oxygen partial pressure is higher in the alveoli than in the red blood cells. As a result, oxygen diffuses from the alveoli through the capillary wall and into the red blood cells.
2. Inside the red blood cells, oxygen reacts with hemoglobin to form oxyhemoglobin and H^+ ions. Oxyhemoglobin formation is favored (according to Le Châtelier's principle) by a high partial pressure of oxygen, a slight cooling of the blood, and an increase in pH (decrease in H^+ ions)—conditions encountered by the blood as it passes through the capillaries of the lungs.
3. Bicarbonate ions (HCO_3^-) diffuse from the plasma into the red blood cells.

rCarner/Shutterstock.com

FIGURE 25.5 Ordinary air contains adequate oxygen to meet our needs, but individuals with breathing difficulties may require supplemental oxygen.

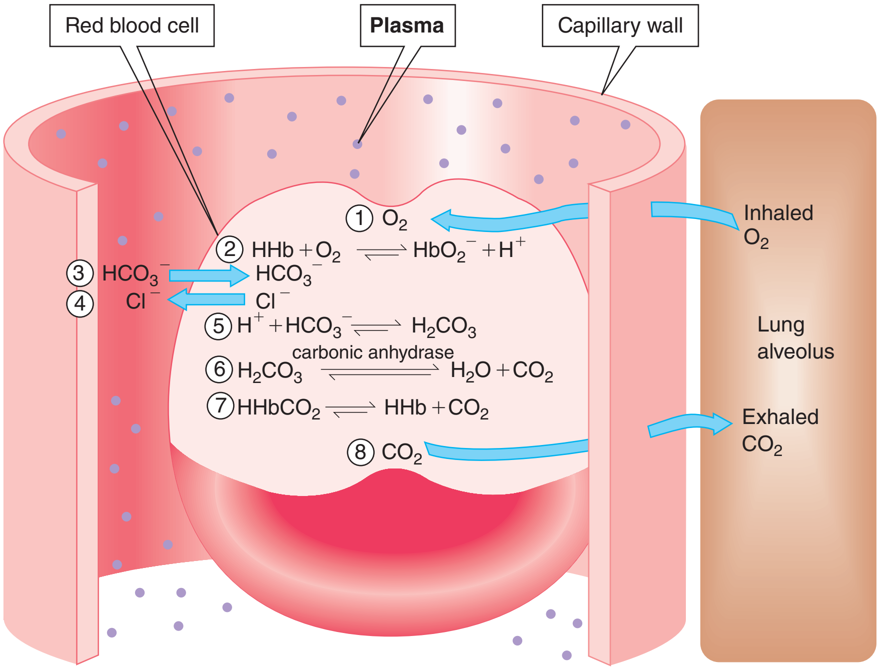

Red blood cell
Plasma
Capillary wall
① O_2
② $HHb + O_2 \rightleftharpoons HbO_2^- + H^+$
③ HCO_3^-
HCO_3^-
④ Cl^-
Cl^-
⑤ $H^+ + HCO_3^- \rightleftharpoons H_2CO_3$
carbonic anhydrase
⑥ $H_2CO_3 \rightleftharpoons H_2O + CO_2$
⑦ $HHbCO_2 \rightleftharpoons HHb + CO_2$
⑧ CO_2
Inhaled O_2
Lung alveolus
Exhaled CO_2

FIGURE 25.6 At the lungs, the carbon dioxide of red blood cells is exchanged for oxygen.

chloride shift The movement of chloride ions from one fluid to another to maintain charge neutrality.

4. The bicarbonate ions are replaced in the plasma by chloride ions that diffuse out of the blood cells. This step, called the **chloride shift**, maintains charge balance and osmotic pressure relationships between the plasma and red blood cells.
5. Protons released by hemoglobin as it is oxygenated (Step 2) react with bicarbonate ions to form carbonic acid.
6. An enzyme in the red blood cells, carbonic anhydrase, promotes the breakdown of carbonic acid to water and carbon dioxide. The reaction is reversible, but the low pressure of carbon dioxide in the lungs favors the formation of carbon dioxide and water (Le Châtelier's principle, again).
7. Carbaminohemoglobin ($HHbCO_2$), formed from hemoglobin and CO_2 at the cellular level, breaks apart to yield hemoglobin and carbon dioxide.
8. Because the carbon dioxide pressure is high in the red blood cells but low in the alveoli, carbon dioxide molecules diffuse out of the red blood cells and into the lung. The carbon dioxide and some of the water formed in Step 6 are expelled in the exhaled air.

Oxygenated red blood cells are carried by the bloodstream into the capillaries surrounding the cells of active tissues. **Figure 25.7** shows the steps involved in delivering oxygen to the tissues and accepting carbon dioxide for transport to the lungs. These steps are essentially the reverse of those at the lungs:

1. Tissue cells use oxygen to produce energy; carbon dioxide and water are formed as byproducts. The concentration of carbon dioxide is higher in the tissue cells than in the red blood cells, so carbon dioxide diffuses from the tissue cells into the interstitial fluid and then into the red blood cells.
2. Inside the red blood cells, carbon dioxide rapidly reacts with water in the presence of carbonic anhydrase to produce carbonic acid.
3. Carbonic acid dissociates to give hydrogen ions and bicarbonate ions.
4. The bicarbonate ions diffuse into the plasma. Most carbon dioxide in the plasma is transported in the bicarbonate ion form, moving from tissue cells to the lungs.
5. The chloride shift again takes place (this time in the opposite direction) to maintain electrolyte balance.
6. A smaller amount (25%) of carbon dioxide from Step 1 reacts with hemoglobin to form carbaminohemoglobin ($HHbCO_2$) for transport to the lungs.
7. The increase in concentration of hydrogen ions inside the red blood cells promotes a reaction with oxyhemoglobin, which releases oxygen.
8. The free oxygen diffuses out of the red blood cells through the plasma, capillary membrane, interstitial fluid, and into the tissue cells.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

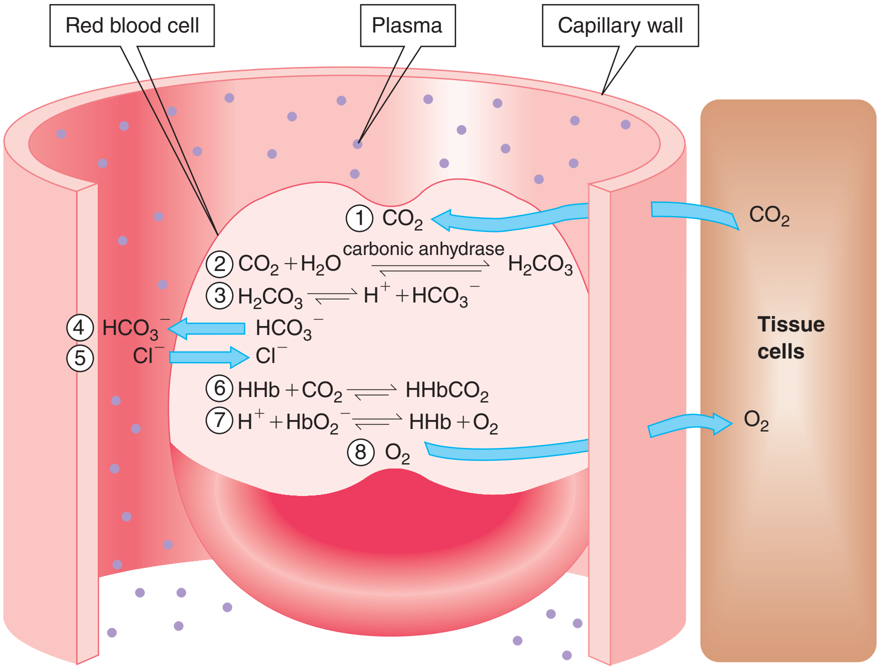

Red blood cell
Plasma
Capillary wall
① CO₂
② CO₂ + H₂O
carbonic anhydrase
H₂CO₃
③ H₂CO₃ ⇌ H⁺ + HCO₃⁻
④ HCO₃⁻
⑤ Cl⁻
HCO₃⁻
Cl⁻
⑥ HHb + CO₂ ⇌ HHbCO₂
⑦ H⁺ + HbO₂⁻ ⇌ HHb + O₂
⑧ O₂
CO₂
Tissue cells
O₂

FIGURE 25.7 At the tissue cells, oxygen of red blood cells is exchanged for carbon dioxide.

Example 25.2 Describing Oxygen and Carbon Dioxide Transport

Decide whether each of the following red blood cell reactions occurs at the lungs or at the site of the tissue cells:

a. $HbO_2^- + H^+ \Longleftrightarrow HHb + O_2$
b. $H_2CO_3 \Longleftrightarrow H^+ + HCO_3^-$
c. $HHb + CO_2 \Longleftrightarrow HHbCO_2$

Solution

a. Tissue cells
b. Tissue cells
c. Tissue cells

✔ **LEARNING CHECK 25.2** Decide whether each of the following red blood cell reactions occurs at the lungs or at the site of the tissue cells:

a. $HHbCO_2 \rightleftarrows HHb + CO_2$
b. $H_2O + CO_2 \rightleftarrows H_2CO_3$
c. $H^+ + HCO_3^- \rightleftarrows H_2CO_3$

25.3 Chemical Transport to the Cells

Learning Objective 3 Explain how materials move from the blood into the body cells and from the body cells into the blood.

For substances to be chemically transported in the body, they must become part of the moving bloodstream. They may dissolve in the water-based plasma (as do sugars, amino acids, ions, and gases to some extent), they may become chemically bonded to cellular components (as do oxygen and carbon dioxide with the hemoglobin of blood cells), or they may form a suspension in the plasma of the blood (as do lipids).

Materials transported by the bloodstream to the cells must move through the capillary wall into the interstitial fluid and through the cell membrane into the cell. The reverse must take place when waste products move from inside tissue cells into the bloodstream. During these processes, capillary walls behave as selectively permeable membranes or filters, allowing water containing dissolved nutrients—including oxygen—to pass in one direction and water containing dissolved wastes to pass in the other direction.

The movement of water and dissolved materials through the capillary walls is governed by two factors. They are the pressure of blood against the capillary walls and the differences in protein concentration on each side of the capillary walls.

The concentration of protein in plasma is much higher than the protein concentration of the interstitial fluid outside the blood vessels. This concentration difference results in an osmotic pressure of about 18 torr, which tends to move fluid into the bloodstream. However, the pumping action of the heart puts the blood under pressure (blood pressure) that is greater at the arterial end of a capillary (about 32 torr) than at the venous end (about 12 torr). Because the blood pressure at the arterial end is higher than the osmotic pressure, the tendency is for a net flow to occur from the capillary into the interstitial fluid (see **Figure 25.8**). The fluid that leaves the capillary contains the dissolved nutrients, oxygen, hormones, and vitamins needed by the tissue cells.

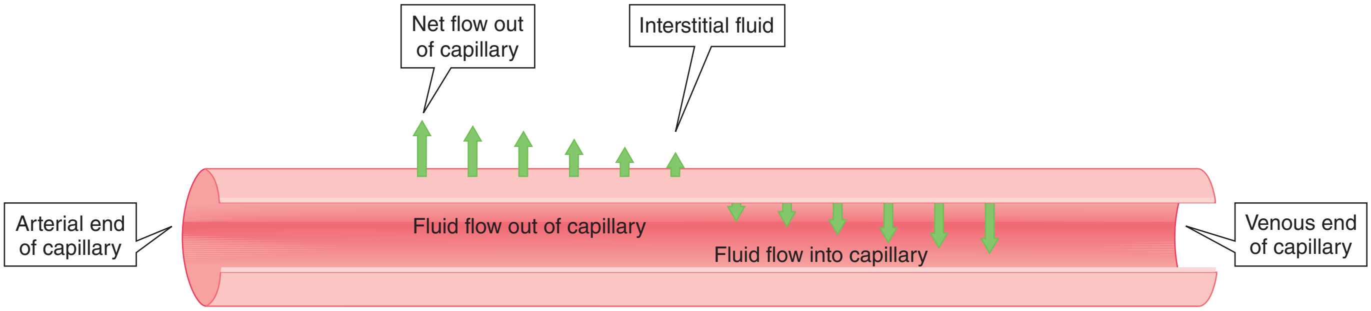

Net flow out of capillary
Interstitial fluid
Arterial end of capillary
Fluid flow out of capillary
Fluid flow into capillary
Venous end of capillary

FIGURE 25.8 The flow of fluid between capillaries and interstitial spaces.

As the blood moves through the capillary, its pressure decreases, until at the venous end, it becomes lower than the osmotic pressure, and a net flow of fluid takes place from the interstitial fluid into the capillary. The incoming fluid contains the metabolic waste products, such as carbon dioxide and excess water. This mechanism allows the exchange of nutrients and wastes and maintains fluid balance between the blood and interstitial space.

TABLE 25.1 Major Dissolved Solids in Normal Urine

Constituent[a]	Grams per 24 Hours[b]
Amino acids	0.80
Urea	25.0
Creatinine	1.5
Uric acid	0.7
H^+	pH 4.5–8.0
Na^+	3.0
K^+	1.7
NH_4^+	0.8
Ca^{2+}	0.2
Mg^{2+}	0.15
Cl^-	6.3
SO_4^{2-}	1.4
$H_2PO_4^-$	1.2
HCO_3^-	0–3
Other compounds	2–3

[a] The 24-hour volume and composition of urine vary widely, depending on the fluid intake and diet.

[b] These data are for an average 24-hour specimen with a total volume of 1400 mL.

25.4 The Constituents of Urine

Learning Objective 4 List the normal and abnormal constituents of urine.

Urine contains about 96% water and 4% dissolved organic and inorganic waste products. Approximately 40 to 50 g of dissolved solids are contained in the daily urine output of an adult (see **Table 25.1**). The urine of a healthy person has a pH of 4.5 to 8.0, with 6.6 being a reasonable average for a person on an ordinary diet. Fruits and vegetables tend to make the urine alkaline, whereas high-protein foods tend to make the urine acidic.

The composition of urine is an excellent indicator of the state of health. This accounts for the importance of urinalysis as part of a physical checkup or a diagnosis. Normal constituents are considered abnormal when they are eliminated in excess amounts. **Table 25.2** lists some conditions that lead to abnormally high urinary levels of normal constituents; some other substances (such as pus or blood), which are considered abnormal in *any* measurable amount, are also listed (see **Figure 25.9**).

A urine specimen is often collected from a patient entering a hospital and is checked with a paper test strip that contains bands of different reagents that will react with the different abnormal constituents. This one simple test quickly checks for indications of pathological conditions.

TABLE 25.2 Some Abnormal Urine Constituents

Abnormal Constituent	Condition	Causes
Glucose (in large amounts)	Glucosuria	Diabetes mellitus, renal diabetes, alimentary glycosuria
Protein	Proteinuria or albuminuria	Kidney damage, nephritis, bladder infection
Ketone bodies	Ketonuria	Diabetes mellitus, starvation, high-fat diets
Pus (leukocytes)		Kidney or bladder infection
Hemoglobin	Hemoglobinuria	Excessive hemolysis of red blood cells
Red blood cells	Hematuria	Hemorrhage in the urinary tract
Bile pigments (in large amounts)	Jaundice	Blockage of bile duct, hepatitis, cirrhosis

Belmonte/BSIP SA/Alamy Stock Photo

FIGURE 25.9 The removal of wastes from the blood is essential to life; hemodialysis helps people with advanced kidney failure.

Example 25.3 Listing Constituents of Urine

a. What is the predominant dissolved solid found in normal urine?
b. What condition is associated with the presence of ketone bodies in urine?
c. What constituent in urine gives rise to hematuria?

Solution

a. Urea
b. Ketonuria
c. Red blood cells

✓ LEARNING CHECK 25.3

a. What is the second most predominant dissolved solid in urine?
b. What constituent in urine can give rise to jaundice?
c. What is the term for glucose found in large amounts in urine?

25.5 Fluid and Electrolyte Balance

Learning Objective 5 Discuss how proper fluid and electrolyte balance is maintained in the body.

The body is 45% to 75% water (by weight); the percentage depends on a number of factors, including age, sex, and especially the amount of body fat. In general, the percentage of water increases as fat content decreases.

Fluid balance within the body is maintained not only by a balance in the total amount but by a normal and stable distribution of fluid in the body's three fluid-containing areas. Thus, the amounts of fluid inside the cells, in the interstitial spaces, and in the blood vessels must remain relatively constant if a fluid balance is to exist.

Fluid and electrolyte balance are interdependent. If one deviates from normal, so does the other. In modern medical practice, a great deal of attention is given to these matters. Many of today's hospital patients receive some form of fluid and electrolyte balance therapy.

An important and obvious principle of fluid balance is that fluid output and intake must be equal. Water from food and drink is absorbed into the body from the digestive tract. Besides this well-known source, water is also derived within the cells from food metabolism. This by-product water enters the bloodstream along with the water that is absorbed from the digestive tract.

HEALTH CONNECTIONS 25.1

Pulse Oximetry

A pulse oximeter measures both the pulse rate and the oxygen saturation level of the blood. This information is used to monitor the breathing of a patient. Monitoring breathing is one method used to determine if a patient's condition is stable, improving, or worsening. Generally, a young healthy individual will have an oxygen saturation level of 95% to 99%. Naturally, this percentage of oxygen saturation varies with age, aerobic fitness, and the altitude at which the person lives and at which the measurement is being made. Because of these characteristics, a single pulse oximetry reading is not very informative. It is much better to make multiple readings over time as a means of monitoring change over that time.

A pulse oximeter determines the quality of breathing by measuring the level of oxygen saturation of the blood. The color of blood changes depending on the amount of oxygen that is attached to each molecule of hemoglobin, i.e., the oxygen saturation of the blood. Highly oxygenated blood is bright red in color, while deoxygenated blood is a deep red color. These changes in color are detected by passing a beam of red light and a beam of infrared light through an extremity such as a finger, toe, or an ear lobe. The amount of light absorbed by the blood changes as the color of the blood changes. Thus, the readings of the pulse oximeter give an indication of the extent of oxygen saturation of the blood, which gives an indication of how well a patient is breathing.

scscsc/Shutterstock.com

A pulse oximeter measures the pulse rate and oxygen concentration of the blood.

Water intake is regulated in part by the thirst mechanism (see **Figure 25.10**). When the body loses large amounts of water, salivary secretions decrease, and a dry feeling develops in the mouth. This and other sensations are recognized as thirst, and water is drunk to relieve the condition. The fluid intake compensates for the fluid lost, and balance is reestablished.

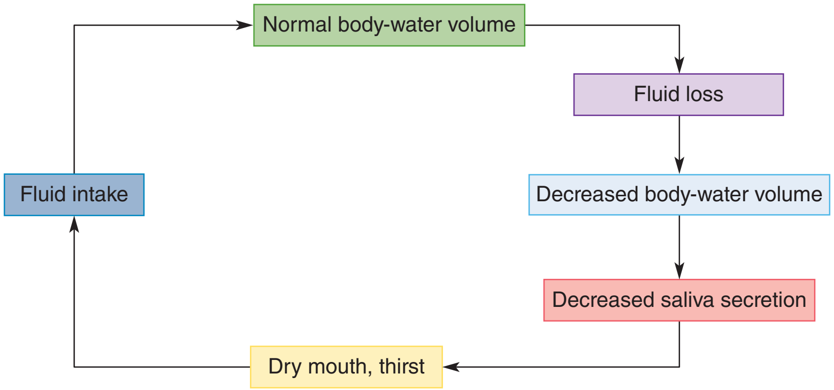


FIGURE 25.10 The thirst mechanism.

TABLE 25.3 Typical Normal Values for Water Entry and Exit

Intake (mL)	
Ingested liquids	1500
Water in foods	700
Water formed by catabolism	200
Total	2400
Output (mL)	
Kidneys (urine)	1400
Lungs (water in expired air)	350
Skin	
By diffusion	350
By perspiration	100
Intestines (in feces)	200
Total	2400

Water normally leaves the body through the kidneys (urine), lungs (water vapor in expired air), skin (by diffusion and perspiration), and intestines (feces) (see **Table 25.3**). Abnormally high fluid losses, and possibly dehydration, can be caused by hyperventilation, excessive sweating, vomiting, or diarrhea.

Fluid balance in the body is maintained or restored primarily by variations in urine output. Normally, this amounts to about 1400 mL/day, but the total excretion fluctuates according to water intake. The primary factor that controls urine production is the rate of water reabsorption from the renal tubules in the kidneys. This rate is regulated chiefly by the pituitary hormone vasopressin and by the adrenal cortex hormone aldosterone.

Vasopressin, also called antidiuretic hormone (ADH), exerts its action by affecting the permeability of the renal tubules to water. In the absence of vasopressin, less water is reabsorbed into the bloodstream, and a large volume of light yellow, dilute urine results. Patients with the rare disease diabetes insipidus do not produce vasopressin; their urine is extremely voluminous and dilute. In the presence of vasopressin, the tubules become more permeable to water that is drawn into the capillaries, thus increasing blood volume. The reabsorption of water from the tubules produces a low volume of dark yellow, concentrated urine. (Diabetes insipidus is very different from diabetes mellitus, mentioned in Health Connections 17.1.)

With the help of vasopressin, a healthy person can vary the intake of water widely and yet preserve a stable overall concentration of substances in the blood. But sometimes the water level of the body gets dangerously low because of not drinking enough water or excessive water loss caused by diarrhea or excessive perspiration. Under such circumstances, the adrenal gland secretes the steroid hormone aldosterone. At the kidneys, aldosterone stimulates the reabsorption of sodium ions (electrolytes) from the renal tubes into the blood. Chloride ions follow the sodium ions to maintain electrical neutrality, and water follows the sodium chloride. Thus, aldosterone secretion conserves both salt and water in the body. When the fluid level of the body returns to normal, the amount of aldosterone secreted decreases.

25.6 Acid–Base Balance

Learning Objective 6 Explain how acid–base balance is maintained in the body.

Blood pH normally remains within the rather narrow range of 7.35 to 7.45. A decrease in pH, called acidosis, or an increase in pH, called **alkalosis**, is serious and requires prompt attention. Death can result when the pH value falls below 6.8 or rises above 7.8 (see **Figure 25.11**). Acidosis, an abnormally low blood pH, was introduced in **Section 24.6**.

alkalosis An abnormally high blood pH.

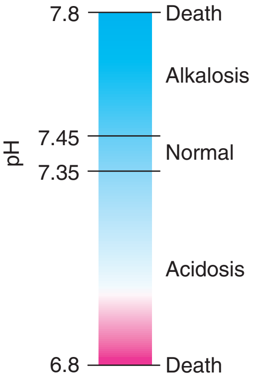


FIGURE 25.11 Human circulatory and respiratory processes operate only within a very narrow range of blood pH.

Large amounts of acids and smaller amounts of bases normally enter the blood. Some mechanisms must neutralize or eliminate these substances if the blood pH is to remain constant. In practice, a constant pH is maintained by the interactive operation of three systems: buffer, respiratory, and urinary. Only when all three parts of this complex mechanism function properly can the acid–base balance be maintained.

25.7 Buffer Control of Blood pH

Learning Objective 7 Explain how buffers work to control blood pH.

A buffer system prevents marked changes in the pH of a solution when an acid or base is added. Three major buffer systems of the blood are the bicarbonate buffer, the phosphate buffer, and the plasma proteins. The most important of these is the bicarbonate buffer system, consisting of a mixture of bicarbonate ions (HCO_3^-) and carbonic acid (H_2CO_3).

Buffer systems work by neutralizing H^+ or OH^- ions that come from the dissociation of acids or bases added to a system. As an example of buffers in action, consider the fate of lactic acid (HLac) entering the bloodstream. When lactic acid dissolves in the blood, it dissociates to produce H^+ and lactate ions (Lac^-). The liberated H^+ ions drive the pH of the blood down. The bicarbonate ions of the bicarbonate buffer system react with the excess H^+ and return the pH to the normal range:

$$\mathrm{HLac} \rightleftharpoons \mathrm{H^+} + \mathrm{Lac^-} \tag{25.3}$$

$$\mathrm{H^+} + \mathrm{HCO_3^-} \rightleftharpoons \mathrm{H_2CO_3} \tag{25.4}$$

Reaction 25.4 is a net ionic reaction for the buffering process. When a total reaction is written, we see that the effect of the buffering is to replace lactic acid in the blood with carbonic acid, which is a weaker acid and so releases fewer H^+ ions to the blood than does lactic acid:

$$\underset{\substack{\text{stronger}\\\text{acid}}}{\mathrm{HLac}} + \mathrm{HCO_3^-} \longrightarrow \underset{\substack{\text{weaker}\\\text{acid}}}{\mathrm{H_2CO_3}} + \mathrm{Lac^-} \tag{25.5}$$

This replacement of a stronger acid with a weaker acid is how biochemists often describe buffering reactions.

Although the bicarbonate system is not the strongest buffer system in the body (the most powerful and plentiful one utilizes the proteins of plasma and cells), it is very important because the concentrations of both bicarbonate and carbonic acid are regulated by the kidneys and by the respiratory system. Without the respiratory and urinary processes, the capacity of buffers would eventually be exceeded.

25.8 Respiratory Control of Blood pH

Learning Objective 8 Describe respiratory control of blood pH.

The respiratory system helps control the acidity of blood by regulating the elimination of carbon dioxide and water molecules. These molecules, exhaled in every breath, come from carbonic acid as follows (see **Figure 25.6**):

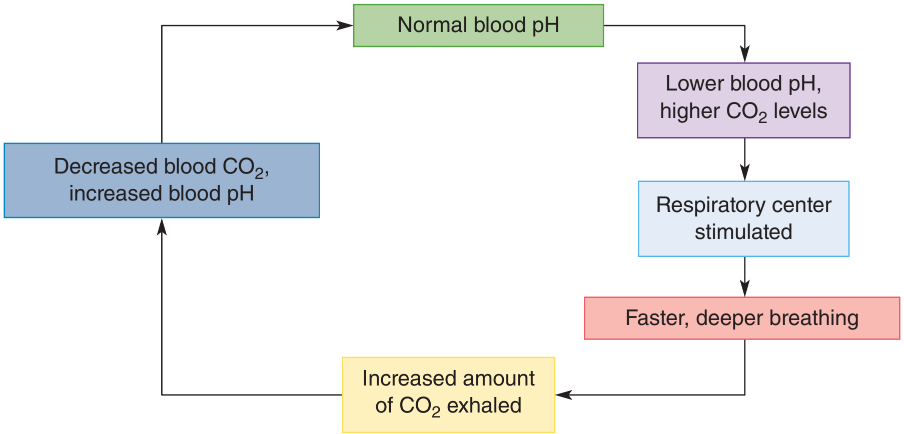
$$\underset{\text{carbonic acid}}{H_2CO_3} \rightleftharpoons H_2O + CO_2 \qquad (25.6)$$

The more CO_2 and H_2O that are exhaled, the more carbonic acid is removed from the blood, thus elevating the blood pH to a more alkaline level.

hyperventilation Rapid, deep breathing.

The respiratory mechanism for controlling blood pH begins in the brain with respiratory center neurons that are sensitive to blood CO_2 levels and pH. A significant increase in the CO_2 of arterial blood, or a decrease below about 7.38 of arterial blood pH, causes the breathing to increase both in rate and depth, resulting in **hyperventilation**. This increased ventilation eliminates more carbon dioxide, reduces carbonic acid and hydrogen-ion concentrations, and increases the blood pH back toward the normal level (see **Figure 25.12**).

FIGURE 25.12 Respiratory control of blood pH.


Normal blood pH
Lower blood pH, higher CO_2 levels
Respiratory center stimulated
Faster, deeper breathing
Increased amount of CO_2 exhaled
Decreased blood CO_2, increased blood pH

hypoventilation Slow, shallow breathing.

In the opposite situation, an increase in blood pH above normal causes **hypoventilation**, a reduced rate of respiration. Less CO_2 is exhaled, and the higher concentration of carbonic acid remaining in the blood lowers the pH back to normal.

25.9 Urinary Control of Blood pH

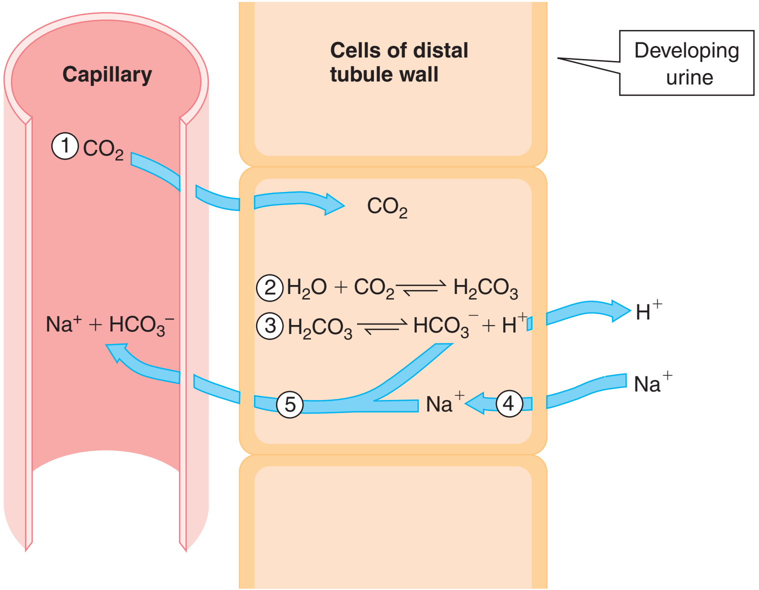
Learning Objective 9 Describe urinary control of blood pH.

Because they can excrete varying amounts of acid and base, the kidneys, like the lungs, play a vital role in pH control. For example, with acidic blood, the excretion of hydrogen ions by the kidneys decreases the urine pH and simultaneously increases the blood pH back toward normal.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Figure 25.13 traces the reactions involved in the excretion of hydrogen ions by the kidneys:

1. Carbon dioxide diffuses from the blood capillaries into the kidney distal tubule cells.
2. Catalyzed by carbonic anhydrase, water and carbon dioxide react to give carbonic acid.
3. The carbonic acid ionizes to give hydrogen ions and bicarbonate ions. The hydrogen ions diffuse into the developing urine.
4. For every hydrogen ion entering the urine, a sodium ion passes into the tubule cells.
5. The sodium ions and bicarbonate ions enter the bloodstream capillaries.



Capillary
Cells of distal tubule wall
Developing urine
① CO_2
CO_2
② $H_2O + CO_2 \rightleftharpoons H_2CO_3$
③ $H_2CO_3 \rightleftharpoons HCO_3^- + H^+$
H^+
$Na^+ + HCO_3^-$
⑤
Na^+
④
Na^+

FIGURE 25.13 Urinary control of blood pH in the kidney.

The net result of these reactions is the conversion of CO_2 to HCO_3^- within the blood. Both the decrease in CO_2 and the increase in HCO_3^- tend to increase blood pH levels back to normal. The developing urine has picked up the hydrogen ions, which now react with buffering ions such as phosphate that are present in urine:

$$H^+ + HPO_4^{2-} \rightarrow H_2PO_4^- \qquad (25.7)$$

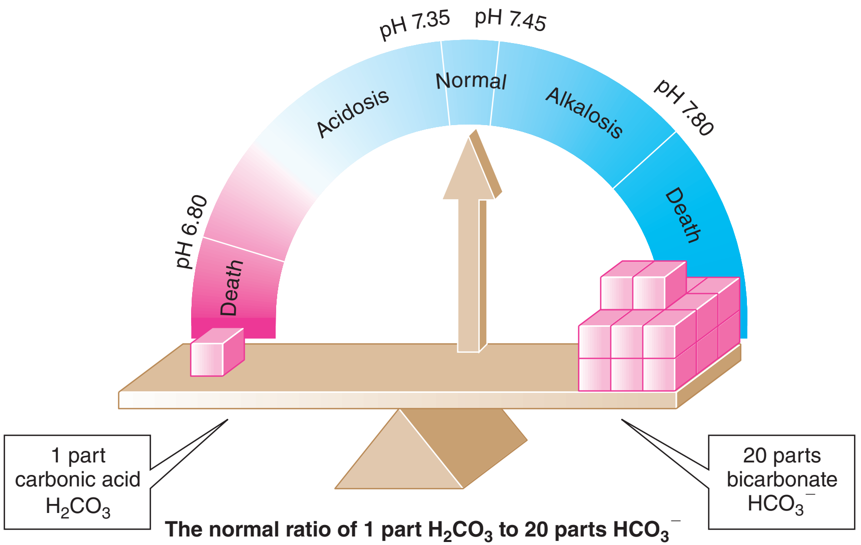
The presence of the phosphate buffer system $H_2PO_4^-/HPO_4^{2-}$ usually keeps urine from going much below pH 6, but too great an excess of protons from carbonic acid can exceed the buffer capacity of the system and result in quite acidic urine.

25.10 Acidosis and Alkalosis

Learning Objective 10 List the causes of acidosis and alkalosis.

When blood pH is normal and a state of acid–base balance exists, components of the bicarbonate buffer are present in plasma in a ratio of 20 parts of bicarbonate (HCO_3^-) to 1 part of carbonic acid (H_2CO_3). When respiratory and urinary systems work together to maintain the blood at pH 7.4, they do so primarily by maintaining the HCO_3^-/H_2CO_3 ratio at 20:1. Any change in the ratio produces a change in pH. An increase in the ratio of bicarbonate to carbonic acid causes the pH to increase (alkalosis); and a decrease in the ratio, which is much more common, causes the pH to decrease (acidosis) (see **Figure 25.14**).

FIGURE 25.14 Blood pH depends on the relative concentrations of carbonic acid and bicarbonate ion.



The normal ratio of 1 part H_2CO_3 to 20 parts HCO_3^- indicating that the body is in acid–base balance

Two adjectives describe the general cause or origin of pH imbalances in body fluids: metabolic and respiratory. Respiratory acid–base imbalances (respiratory acidosis and respiratory alkalosis) result from abnormal breathing patterns. Metabolic acidosis and metabolic alkalosis are caused by factors other than abnormal breathing.

25.10A Respiratory Alkalosis

respiratory alkalosis A condition of alkalosis caused by hyperventilation.

Respiratory alkalosis is caused by hyperventilating—breathing rapidly and deeply. Hysteria, anxiety, or prolonged crying may result in hyperventilation in which too much carbon dioxide is exhaled, which disturbs the blood's normal carbon dioxide/carbonic acid ratio. According to Le Châtelier's principle, Reaction 25.6 (written again below as part of Reaction 25.8) shifts to the right as it attempts to restore the equilibrium:

$$\underset{\substack{\xrightarrow{\hspace{6em}} \\ \text{direction of shift to} \\ \text{restore equilibrium}}}{H_2CO_3 \rightleftharpoons H_2O + \overset{\textit{loss of } CO_2}{CO_2 \uparrow}} \qquad (25.8)$$

The equilibrium shift reduces the amount of carbonic acid present and rapidly increases the HCO_3^-/H_2CO_3 ratio to a value greater than 20:1. As a result, blood pH rises to 7.54 or higher within a few minutes. A corresponding loss of HCO_3^- also occurs, but it is not large enough to maintain the HCO_3^-/H_2CO_3 ratio at 20:1. The treatment of respiratory alkalosis involves rebreathing one's own exhaled air by breathing into a paper bag (*not* a plastic bag), administering carbon dioxide, and treating the underlying causes of the hyperventilation.

25.10B Respiratory Acidosis

respiratory acidosis A condition of acidosis caused by hypoventilation.

Respiratory acidosis is sometimes the result of slow or shallow breathing (hypoventilation) caused by an overdose of narcotics or barbiturates. Anesthetists need to be particularly aware of respiratory acidosis, because most inhaled anesthetics depress respiration rates. Lung diseases, such as emphysema and pneumonia, or an object lodged in the windpipe can also result in hypoventilation. In respiratory acidosis, too little carbon dioxide is exhaled, and its concentration within the blood increases. The carbon dioxide/carbonic acid equilibrium shifts to the left to restore the equilibrium:

$$\underset{\substack{\xleftarrow{\hspace{6em}} \\ \text{direction of shift} \\ \text{of equilibrium}}}{H_2CO_3 \rightleftharpoons H_2O + \overset{\textit{increased } CO_2}{CO_2}} \qquad (25.9)$$

As a result of the shift, the concentration of carbonic acid in the blood increases, the HCO_3^-/H_2CO_3 ratio decreases to less than 20:1, and respiratory acidosis sets in. The treatment of respiratory acidosis involves identifying the underlying causes and possibly the intravenous administration of isotonic sodium bicarbonate solution or hemodialysis.

25.10C Metabolic Acidosis

Various body processes—collectively called metabolism—produce acidic substances that liberate H^+ in solution. The diffusion of these substances into the bloodstream causes a shift in the carbonic acid–bicarbonate equilibrium:

$$\underset{\substack{\xleftarrow{\qquad\qquad\qquad\qquad} \\ \text{direction of shift to} \\ \text{restore equilibrium}}}{H_2CO_3 \rightleftarrows \overset{\textit{increased } H^+}{H^+} + HCO_3^-} \tag{25.10}$$

The shift decreases the concentration of bicarbonate ions and increases the concentration of carbonic acid. As a result, the HCO_3^-/H_2CO_3 ratio decreases, as does the blood pH. **Metabolic acidosis** is often a serious problem in uncontrolled diabetes mellitus, and it also occurs temporarily after heavy exercise. Other causes include severe diarrhea and aspirin overdose.

metabolic acidosis A condition of acidosis resulting from causes other than hypoventilation.

Symptoms of metabolic acidosis, besides low blood pH and high levels of H_2CO_3, include the following: hyperventilation as the respiratory center tries to get excess CO_2 out of the lungs, increased urine formation as the kidneys try to remove excess acids, thirst (to replace urination water loss), drowsiness, headache, and disorientation. The treatment again depends on the cause; it may involve insulin therapy, intravenous bicarbonate, or hemodialysis. Note carefully that hyperventilation can be a symptom of metabolic acidosis and a cause of respiratory alkalosis, two different conditions requiring very different treatments.

25.10D Metabolic Alkalosis

In **metabolic alkalosis**, the body has lost acid in some form, perhaps from prolonged vomiting of the acidic stomach contents, or there has been an ingestion of alkaline substances. Excessive use of sodium bicarbonate (baking soda), for example, a common home remedy for upset stomach, increases the concentration of bicarbonate ions in the blood.

metabolic alkalosis A condition of alkalosis resulting from causes other than hyperventilation.

A decrease in acid concentration within the body (from vomiting) or an increase in HCO_3^- levels (from excessive $NaHCO_3$) causes the HCO_3^-/H_2CO_3 ratio to rise above 20:1, and measurable alkalosis is observed. The respiratory center responds to the higher blood pH by slowing the breathing (hypoventilation). Other symptoms may include numbness, tingling, and headache. **Table 25.4** is a summary of causes of acidosis and alkalosis.

TABLE 25.4 Some Causes of Blood Acid–Base Imbalance

Condition	Causes
Respiratory	
Acidosis: $CO_2 \uparrow$ pH $\downarrow$	Hypoventilation, blockage of diffusion within lungs, respiratory center depressants
Alkalosis: $CO_2 \downarrow$ pH $\uparrow$	Hyperventilation, excitement, trauma
Metabolic	
Acidosis: $H^+ \uparrow$ pH $\downarrow$	Kidney failure, prolonged diarrhea, ketone bodies from diabetes mellitus
Alkalosis: $H^+ \downarrow$ pH $\uparrow$	Kidney disease, prolonged vomiting, excessive intake of baking soda

Example 25.4 Listing Causes of Acidosis and Alkalosis

Decide whether each of the following can give rise to acidosis or alkalosis:

a. Hypoventilation
b. Prolonged vomiting
c. Buildup of ketone bodies

Solution

a. Acidosis b. Alkalosis c. Acidosis

✔ **LEARNING CHECK 25.4** Decide whether each of the following can give rise to acidosis or alkalosis:

a. Hyperventilation
b. Prolonged diarrhea
c. Excessive intake of baking soda

Health Career Description

PERFUSIONIST

Perfusionists take over the role of the heart, lungs, and lymphatic system during surgeries and other procedures and treatments. Without cardiac perfusionists, open-heart surgery would not be possible.

According to the Mayo Clinic, perfusionists hold the following roles and responsibilities:

- Studying the patient's medical history and notes to be prepared for the surgery
- Operating and selecting a variety of extracorporeal circulation equipment, such as the heart-lung machine, the artificial heart, blood transfusion devices, the intra-aortic balloon pump, and various ventricular-assist devices
- Monitoring and care of the patient during surgery to ensure safe physiologic functions
- Routine administration of various types of blood products and medications during surgery
- A variety of administrative duties, such as equipment management, supply purchasing, department management, and quality improvement

The majority of perfusionists work a typical 40-hour-per-week schedule, but they may be required to work shifts, including days, nights, weekends, and holidays.

To become a perfusionist, one must first obtain an AS degree in allied health professions, or a BS degree in biological sciences, then attend a perfusion training program. Some of these programs provide a certificate to supplement an existing degree or consist of a bachelor's degree program entered into after the AS in health professions. The student must then obtain certification through the American Board of Cardiovascular Perfusion (ABCP).

Because of an increase in the population of individuals over the age of 65, the field of perfusion is expected to grow. Currently, the median salary for this highly skilled career is $124,000.

Sources: ExploreHealthCareers.org. (n.d.). Pediatric Nurse. Retrieved July 18, 2020 from https://explorehealthcareers.org/career/nursing/pediatric-nurse/; Bureau of Labor Statistics, U.S. Department of Labor. Occupational Outlook Handbook, Registered Nurse. Retrieved July 18, 2020 from https://www.bls.gov/ooh/healthcare/registered-nurses.htm/

Concept Summary

25.1 A Comparison of Body Fluids

Learning Objective: Can you compare the chemical composition of plasma, interstitial fluid, and intracellular fluid?

- Most fluids of the body are located in three regions of the body:
  - Inside tissue cells (intracellular fluid)
  - Outside tissue cells (extracellular fluid)
  - In blood vessels.
- Volumetrically, most of the extracellular fluids (outside tissue cells) are of two types—blood and interstitial fluid.
- Interstitial fluid occupies spaces between cells and moves in the lymph vessels.
- Other extracellular body fluids that occur in smaller amounts are urine, digestive juices, and cerebrospinal fluid.
- Chemically, blood (plasma) and interstitial fluid (including lymph) are similar.
- Intracellular fluid is chemically different from extracellular fluid.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

25.2 Oxygen and Carbon Dioxide Transport

Learning Objective: Can you explain how oxygen and carbon dioxide are transported within the bloodstream?

- Nearly all oxygen that is transported from the lungs to tissue cells is transported by the blood in the form of oxyhemoglobin.
- Most carbon dioxide transported from the cells to the lungs is transported by the blood in the form of bicarbonate ions dissolved in the plasma.
- Smaller amounts also travel as carbaminohemoglobin and as CO_2 gas dissolved in plasma.
- The formation of the two hemoglobin compounds and the dissolving of various materials in the plasma are influenced by equilibria related to concentration differences of materials in the blood as it passes through capillaries in the lungs or near tissue cells.

25.3 Chemical Transport to the Cells

Learning Objective: Can you explain how materials move from the blood into the body cells and from the body cells into the blood?

- Substances transported by the blood to tissue cells move from the blood, through capillary walls, into the interstitial fluid, then through cell membranes, and finally into the cytoplasm of the cells.
- Waste products of the cells move in the opposite direction.
- The movement of fluid through capillary walls is governed by the blood pressure against the capillary walls and by osmotic pressure differences that arise from protein concentration differences between blood and interstitial fluid.

25.4 The Constituent of Urine

Learning Objective: Can you list the normal and abnormal constituents of urine?

- Normal urine is about 96% water and 4% dissolved organic and inorganic wastes.
- Because urine composition is an excellent indicator of a person's health, urinalysis is a routine procedure in physical checkups.

25.5 Fluid and Electrolyte Balance

Learning Objective: Can you discuss how proper fluid and electrolyte balance is maintained in the body?

- Fluid balance in the body involves a balance between fluid intake and output and proper distribution of fluid among the three fluid areas.
- Fluid and electrolyte balance are interdependent.
- Water enters the body through food and drink and leaves in the form of urine, water vapor in exhaled air, perspiration, and feces.
- The amount of fluid in the body is maintained or restored primarily by variations in urine output, which is regulated chiefly by the hormones vasopressin and aldosterone.

25.6 Acid–Base Balance

Learning Objective: Can you explain how acid–base balance is maintained in the body?

- Blood pH is normally in the range of 7.35 to 7.45.
- Three systems cooperate to maintain the pH in this narrow range.
- Acidosis and alkalosis exist when the blood pH becomes lower or higher, respectively, than the normal values.

25.7 Buffer Control of Blood pH

Learning Objective: Can you explain how buffers work to control blood pH?

- The blood contains three major buffer systems: the bicarbonate system, the phosphate system, and the plasma protein system.
- The most important is the bicarbonate system, which consists of a mixture of bicarbonate ions and carbonic acid.

25.8 Respiratory Control of Blood pH

Learning Objective: Can you describe respiratory control of blood pH?

- The respiratory system influences blood pH by regulating the elimination of carbon dioxide and water.
- Because carbon dioxide and water are produced during the decomposition of carbonic acid, the greater the elimination of carbon dioxide and water from the body, the greater is the elimination of carbonic acid from the blood.

25.9 Urinary Control of Blood pH

Learning Objective: Can you describe urinary control of blood pH?

- The kidneys influence blood pH by varying the amount of hydrogen ions excreted in the urine.
- When the blood is too acidic, carbonic acid is converted to bicarbonate ions and hydrogen ions.
- The hydrogen ions are excreted, and the bicarbonate ions enter the blood.

25.10 Acidosis and Alkalosis

Learning Objective: Can you list the causes of acidosis and alkalosis?

- Acidosis and alkalosis can result from metabolic or respiratory causes.
- Respiratory acidosis and alkalosis are the result of abnormal breathing patterns.
- Alkalosis is caused by hyperventilation that accompanies hysteria, anxiety, or prolonged crying.
- Acidosis can result from hyperventilation brought on by such factors as an overdose of depressant narcotics or anesthesia.
- Metabolic acidosis can result from the metabolic production of acids in the body or the elimination of alkaline materials, as during severe diarrhea.
- Metabolic alkalosis results from the loss of acid in some form such as the prolonged vomiting of acidic stomach contents or the ingestion of alkaline materials.

Key Terms and Concepts

Alkalosis (25.6)
Carbaminohemoglobin (25.2)
Chloride shift (25.2)
Deoxyhemoglobin (hemoglobin) (25.2)
Extracellular fluid (25.1)
Hyperventilation (25.8)
Hypoventilation (25.8)
Interstitial fluid (25.1)
Intracellular fluid (25.1)
Metabolic acidosis (25.10)
Metabolic alkalosis (25.10)
Oxyhemoglobin (25.2)
Plasma (25.1)
Respiratory acidosis (25.10)
Respiratory alkalosis (25.10)

Key Equations

1. Formation of oxyhemoglobin (**Section 25.2**):	$HHb + O_2 \rightleftarrows HbO_2^- + H^+$	Reaction 25.1
2. Formation of carbaminohemoglobin (**Section 25.2**):	$HHb + CO_2 \rightleftarrows HHbCO_2$	Reaction 25.2
3. Decomposition of carbonic acid (**Section 25.8**):	$H_2CO_3 \rightleftarrows H_2O + CO_2$	Reaction 25.6

Exercises

Even-numbered exercises are answered in Appendix B.

Exercises with an asterisk (*) are more challenging.

A Comparison of Body Fluids (Section 25.1)

25.1 Where is most fluid in the body located? What is it called?

25.2 Which two of the following have nearly the same chemical composition: plasma, intracellular fluid, interstitial fluid?

25.3 In what way does the composition of the two similar fluids in Exercise 25.2 differ?

25.4 Which of the fluids of Exercise 25.2 contains the highest concentration of the following?

a. Protein
b. K^+
c. Na^+
d. HPO_4^{2-}

25.5 Which of the fluids of Exercise 25.2 contains the highest concentration of the following?

a. SO_4^{2-}
b. HCO_3^-
c. Mg^{2+}
d. Cl^-

25.6 What is the principal cation found in the following?

a. Blood plasma
b. Interstitial fluid
c. Intracellular fluid

25.7 What is the principal anion in the following?

a. Blood plasma
b. Interstitial fluid
c. Intracellular fluid

25.8 What is the principal type of organic compound found in intracellular fluid?

Oxygen and Carbon Dioxide Transport (Section 25.2)

25.9 Write a reversible chemical equation that shows the reaction of hemoglobin (Hb) with:

a. Oxygen
b. Carbon dioxide

25.10 Why is Le Châtelier's principle so important in the transport of O_2 and CO_2 in the bloodstream?

25.11 Why can't all of the oxygen required by the body travel in the bloodstream as oxygen gas?

25.12 Hemoglobin exists in several forms—oxyhemoglobin, deoxyhemoglobin, and carbaminohemoglobin. Match each of the following to the type of hemoglobin involved:

a. Formed when CO_2 combines with hemoglobin
b. The oxygen-transporting form of hemoglobin
c. The form of hemoglobin designated as HHb

25.13 What percentages of the total O_2 and CO_2 transported by the blood are in the following forms?

a. O_2 as dissolved gas in plasma
b. O_2 as oxyhemoglobin
c. CO_2 as carbaminohemoglobin
d. CO_2 as dissolved gas in plasma
e. CO_2 as bicarbonate ions

25.14 What term is given to the reversible flow of chloride ions across the red blood cell membrane during the oxygen and carbon dioxide transport process?

25.15 Carbon monoxide (CO) can bind to the iron of hemoglobin and cause carbon monoxide poisoning. How might the high-pressure oxygen exposure of a hyperbaric chamber help treat the patient?

25.16 Why are large capillary surface areas critical to O_2 and CO_2 transport processes? What driving force causes O_2 to move from lung alveoli into the bloodstream and CO_2 to move from the bloodstream into lung alveoli?

25.17 Write the equilibrium equation representing the reaction between oxygen and hemoglobin. In which direction will the equilibrium shift when the following occurs?

a. The pH is increased.

b. The concentration (pressure) of O_2 is increased.

c. The concentration of CO_2 is increased (see **Figure 25.6**).

d. The blood is in a capillary near actively metabolizing tissue cells.

Chemical Transport to the Cells (Section 25.3)

25.18 Which factor, blood pressure or osmotic pressure, has the greater influence on the direction of fluid movement through capillary walls at (a) the venous end of a capillary and (b) the arterial end of a capillary?

25.19 What chemical substances are transported as a suspension in the plasma of the blood?

25.20 What substances give rise to the osmotic pressure difference between the bloodstream and interstitial fluid?

25.21 What types of compounds leave the capillaries and enter the interstitial fluid? What types of compounds leave the interstitial fluid and enter the capillaries to be transported away?

The Constituents of Urine (Section 25.4)

25.22 What organic material is normally excreted in the largest amount in urine?

25.23 What cation and anion are normally excreted in the largest amounts in urine?

25.24 Why does the pH of urine have a larger normal range than blood?

25.25 What condition might result from an excessive hemolysis of red blood cells?

25.26 What might cause proteins to be present in urine?

25.27 List the abnormal constituents of urine.

25.28 Under what circumstances would the presence of a normal constituent of urine be considered abnormal?

Fluid and Electrolyte Balance (Section 25.5)

25.29 List four routes by which water leaves the body.

25.30 What are three sources of water that contribute to the fluid intake of a human body?

25.31 What is the primary way fluid balance is maintained in the body?

25.32 List four possible causes of dehydration.

25.33 For a hydrated body, if you ingest more liquid in a day than you need, which area of output will most likely increase?

25.34 Vasopressin can be affected by alcohol, causing it to be less effective. What would be the impact on water reabsorption?

25.35 Describe how vasopressin and aldosterone function to maintain fluid levels in the blood.

25.36* Trace the events of the regulation of fluid balance by the thirst mechanism.

Acid–Base Balance (Section 25.6)

25.37 What is the normal pH range of human blood? Outside what pH range will death occur?

25.38 List three systems that cooperate to maintain blood pH in an appropriate narrow range. Which one of these provides the most rapid response to changes in blood pH?

25.39 What is meant by the terms *acidosis* and *alkalosis*?

Buffer Control of Blood pH (Section 25.7)

25.40 List three major buffer systems of the blood.

25.41 What are the two components of the most important buffer system?

25.42 Why are two components needed in buffering systems?

25.43 What is said to be the strongest buffer system in the blood?

25.44 Can the capacity of the blood buffering systems be exceeded? Explain your answer.

25.45 Explain how the reaction of a strong acid with bicarbonate serves to buffer the blood.

25.46* Hemoglobin (HHb) is a weak acid that forms the Hb^- anion. Write equations to show how the HHb/Hb^- buffer would react to added H^+ and added OH^-.

Respiratory Control of Blood pH (Section 25.8)

25.47 Describe the respiratory mechanism for controlling blood pH.

25.48 Hyperventilation is a symptom of what type of acid–base imbalance in the body?

25.49 What impact does breathing out CO_2 have on the pH of the blood?

25.50 Hypoventilation is a symptom of what type of acid–base imbalance in the body?

Urinary Control of Blood pH (Section 25.9)

25.51 Write a short summary description of the role of the kidneys and urine in the control of blood pH.

25.52 What happens to CO_2 in the blood when the kidneys function to control blood pH?

25.53 What happens to blood pH as HCO_3^- increases?

25.54 What buffer system in the urine usually keeps the urine pH from dropping lower than 6?

25.55 What ionic shift maintains electron charge balance when the kidneys function to increase the pH of blood?

Acidosis and Alkalosis (Section 25.10)

25.56 What is the normal ratio of bicarbonate to carbonic acid in the blood?

25.57 What is the difference between the causes of respiratory acid–base imbalances and metabolic acid–base imbalances in the body?

25.58 What type of acid–base imbalance in the blood is caused by hypoventilation? By hyperventilation?

25.59 Breathing too fast causes a rise in blood pH. Explain why.

25.60 Breathing too slowly causes a drop in blood pH. Explain why.

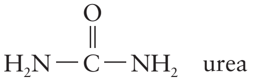
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

25.61 What type of acid–base imbalance might develop in an individual who has taken an overdose of a depressant narcotic? In an individual with uncontrolled diabetes mellitus?

25.62 Explain how prolonged vomiting can lead to alkalosis.

Additional Exercises

25.63 An average adult excretes about 25.0 g of urea in his or her urine daily. Assuming both nitrogen atoms of the urea molecule come from the deamination of amino acids (one N atom/amino acid), how many amino acid molecules were deaminated to produce this amount of urea?



$$H_2N-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2 \quad \text{urea}$$

25.64 A person inhales O_2 and exhales CO_2. What is the ultimate use for the O_2 in the cell? Is the O_2 that we inhale incorporated into the CO_2 we exhale? What is the source of the CO_2 we exhale?

25.65 When the body is dehydrated, aldosterone causes the active reabsorption of Na^+ ions from the renal tubules into the blood, which causes water to "follow" the Na^+ ions into the blood. Explain what causes this flow of water to occur.

25.66 The body uses the phosphate buffer system shown in the following reaction (a).

$$H^+ + HPO_4^{2-} \rightleftarrows H_2PO_4^- \text{ (a)}$$

$$H^+ + H_2PO_4^- \rightleftarrows H_3PO_4 \text{ (b)}$$

Explain why reaction (b) is not used in the human body as a buffer system. (*Hint*: What are the pKa values for the dissociations of the individual hydrogen ions?)

25.67 Explain how heavy exercise can cause metabolic acidosis.

Chemistry for Thought

25.68 Explain why a hysterical individual might develop alkalosis.

25.69 When you lose a pound of fat, in what form do those molecules leave the body?

25.70 When a person starts to become dehydrated, they first lose fluids in the interstitial spaces. How would this affect the concentration of interstitial fluid components?

25.71 Women have 6–11% more body fat than men. Women have less fluid (55%) than men (60%). Hypothesize how the percentage of fat cells may affect water storage.

25.72 Why do the number of cations and anions in any fluid compartment need to be equal?

25.73 What happens to the pH of a carbonated beverage as CO_2 escapes?

25.74 What structural features of proteins enable them to serve as buffers?

25.75 Why is the choice of lactic acid appropriate for the discussion in **Section 25.7**?

25.76 No system in our body works independently. Explain how blood buffering systems work together.

25.77 Alkaline diets have been a fad. Does eating alkaline foods increase your blood pH? Explain your answer.

25.78 Explain why a person suffering from metabolic acidosis might develop a thirst.

25.79 Ordinary water may be the most effective "sports drink." Explain why this might be true.

25.80 How does the concentration of hemoglobin of someone living in the Himalayas compare with that of someone living at a lower altitude?

25.81 What happens if the amount of H+ ions in the urine exceeds urine's buffering capacity?

25.82 Aerobic exercise causes your cells to produce CO_2 and H_2O. Why can you dehydrate during aerobic exercise even if you don't perspire?

25.83 What types of food can make urine acidic? What types of food will make it basic?

25.84 Explain how uncontrolled diarrhea can lead to acidosis.

APPENDIX A

The International System of Measurements

The International System of Units (SI units) was established in 1960 by the International Bureau of Weights and Measures. The system was established in an attempt to streamline the metric system, which included certain traditional units that had historical origins but that were not logically related to other metric units. The International System established fundamental units to represent seven basic physical quantities. These quantities and the fundamental units used to express them are given in Table A.1.

TABLE A.1 Fundamental SI Units

Physical Quantity	SI Unit	Abbreviation
Length	meter	m
Mass	kilogram	kg
Temperature	kelvin	K
Amount of substance	mole	mol
Electrical current	ampere	A
Time	second	s
Luminous intensity	candela	cd

All other SI units are derived from the seven fundamental units. Prefixes are used to indicate multiples or fractions of the fundamental units (Table 1.2). In some cases, it has been found convenient to give derived units specific names. For example, the derived unit for force is kg m/s^2, which has been given the name newton (abbreviated N) in honor of Sir Isaac Newton (1642–1727). Some examples of derived units are given in Table A.2.

TABLE A.2 Examples of Derived SI Units

Physical Quantity	Definition in Fundamental Units	Specific Name	Abbreviation
Volume	m^3 (see NOTE below)	—	—
Force	kg m/s^2	newton	N
Energy	kg m^2/s^2 = N m	joule	J
Power	kg m^2/s^3 = J/s	watt	W
Pressure	kg/m s^2 = N/m^2	pascal	Pa
Electrical charge	A s	coulomb	C
Electrical potential	kg m^2/A s^3 = W/A	volt	V
Electrical resistance	kg m^2/A^2 s^3 = V/A	ohm	Ω
Frequency	1/s	hertz	Hz

NOTE: The liter (L), a popular volume unit of the metric system, has been redefined in terms of SI units as 1 dm^3 or 1/1000 m^3. It and its fractions (mL, μL, etc.) are still widely used to express volume.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

APPENDIX B

Answers to Even-Numbered End-of-Chapter Exercises

Chapter 1

1.2 Mass is a measurement of the amount of matter in an object. Weight is a measurement of the gravitational force acting on an object.

1.4 **a.** The distance the ball could be thrown on the moon would be greater. Although the throwing force would be the same, the smaller gravitational force pulling the ball downward would allow the ball to travel farther before hitting the surface of the moon.

b. The rolling distance would be the same in both locations because gravity does not influence rolling motion on a smooth surface.

1.6 The gravitational force is greater the closer an object is to the center of Earth. Thus, a person would weigh more at the poles (closer to the center) and less at the equator.

1.8 **a.** Physical: Both pieces of the stick are still made of the same substance.

b. Chemical: The smoke is a new substance.

c. Physical: Each smaller piece is still the substance salt.

d. Chemical: The change in color indicates a change in the substances present.

1.10 **a.** Physical: The state of a substance (solid, liquid, or gas) can be changed without changing the identity of the substance.

b. Chemical: The word *reacts* indicates a chemical change.

c. Physical: Freezing is a physical change, so the temperature at which it occurs is a physical property.

d. Chemical: Because rusting is a chemical change (rust is a different substance from the metal), the ability to rust or not to rust is a chemical property.

e. Physical: Color is a physical property because it can be observed without trying to change the substance into another substance.

1.12 **a.** Yes. The change in melting point indicates a different substance has been formed. Also, the evolved gas is a different substance.

b. No. It must be different because its melting point is different from that of aspirin.

c. The aspirin molecules must be larger because the atoms of the aspirin were divided between the molecules of the new solid and the molecules of the evolved gas.

d. Heteroatomic, because the aspirin changed into two different substances, molecules of aspirin must contain at least two different kinds of atoms.

1.14 Heteroatomic: Because only a single substance is formed, its molecules must contain at least one atom from each of the two reacting substances.

1.16 Heteroatomic: The molecules of the products hydrogen and oxygen contain hydrogen atoms and oxygen atoms, respectively. The two different kinds of atoms must have come from the water.

1.18 **a.** A is a compound because compounds are made up of heteroatomic molecules.

b. D is an element because elements are made up of homoatomic molecules.

c. E is a compound because it can be changed into the simpler substances G and J. The simpler substances G and J cannot be classified without conducting further tests on them to see if they can be changed into other, still simpler substances.

1.20 **a.** R cannot be classified as an element or a compound. Even though none of the tests changed it into a simpler substance, all possible tests were not done on it, and some test might exist that would change it.

b. T can be classified as a compound because it was changed into simpler substances.

c. The remaining solid cannot be classified because no tests were done to see if it could be changed into simpler substances.

1.22 **a.** heterogeneous

b. homogeneous

c. homogeneous

d. heterogeneous

e. homogeneous

f. homogeneous

g. heterogeneous

1.24 **b.** solution

c. solution

e. solution

f. solution

1.26 In a modern society, quantities must be expressed with precision. Goods, services, time, and so on must be clearly expressed as quantities in order for trade, purchases, salaries, and the like to be carried out or determined.

1.28 The stone would be useful for expressing relatively large quantities such as the weights of people, cows, or bags of grain. It is likely that originally “one stone” was equal to the weight of some field stone that had been accepted as a standard.

1.30 **a.** Metric

b. Metric

c. Nonmetric

d. Metric

e. Nonmetric

f. Metric

1.32 **c.** Meters

e. Liters

1.34 **a.** 1 million μL

b. 75 thousand watts

c. 15 million hertz

d. 200×10^{-12} meters

1.36 0.240 L, 240 cm^3

1.38 8.8 lb

1.40 **a.** About 3 in.

b. 65 K

c. About 2 kg

1.42 **a.** 1.0 g/cm^3

b. 68 oz

c. 330 mg

1.44 97.0°F in the morning and 99.0°F at bedtime

1.46 **a.** Incorrect: No zero should precede the first number in the nonexponential number. 2.7×10^{-3} is correct.

b. Correct

c. Incorrect: The decimal is not in the standard position in the nonexponential number. 7.19×10^{-5} is correct.

d. Incorrect: No nonexponential number is given. 1×10^3 is correct.

e. Incorrect: The decimal is not in the standard position in the nonexponential number. 4.05×10^{-4} is correct.

f. Incorrect: No exponent is used, and the decimal is not in the standard position in the nonexponential number. 1.19×10^{-1} is correct.

1.48 **a.** 1.4×10^4

b. 3.65×10^2

c. 2.04×10^{-3}

d. 4.618×10^2

e. 1.00×10^{-3}

f. 9.11×10^2

1.50 1.86×10^5 mi/s; 1.100×10^9 km/h

1.52 0.000 000 000 000 000 000 000 105

1.54 **a.** 9.0×10^{-5}

b. 1.4×10^7

c. 7.6×10^{-2}

d. 1.9×10^1

e. 2.6×10^{12}

1.56 **a.** $(1.44 \times 10^2)(8.76 \times 10^{-2}) = 1.26 \times 10^1$

b. $(7.51 \times 10^2)(1.06 \times 10^2) = 7.96 \times 10^4$

c. $(4.22 \times 10^{-2})(1.19 \times 10^{-3}) = 5.02 \times 10^{-5}$

d. $(1.28000 \times 10^5)(3.16 \times 10^{-5}) = 4.04 \times 10^0$

1.58 **a.** 2.6×10^{-5}

b. 2.2×10^2

c. 6.4×10^{-4}

d. 7.25×10^{-4}

e. 3.1×10^{-2}

1.60 **a.** 1.7×10^{-1}

b. 1.0×10^{-9}

c. 2.6×10^6

d. 2.3×10^0

e. 1.5×10^7

1.62 **a.** 0.01 cm

b. 0.01 mm

c. 0.1°

d. 0.1 lb/in.^{2}

1.64 **a.** 6.0 mL

b. 37.00°C

c. 9.00 g

d. 15.5 degrees

1.66 **a.** Measured: 5.06 lb; exact: 16 potatoes; 0.316 lb/potato

b. Measured: the individual percentages; exact: the 5 players; 71.34%/player. Note that the sum of the five percentages has four significant figures, so the calculated average must have four.

1.68 **a.** 3

b. 3

c. 4

d. 2

e. 4

f. 5

1.70 **a.** 5.2

b. 0.104

c. 0.518

d. 1.0×10^2

e. 2.52×10^{-18}

1.72 **a.** 6.2

b. 230

c. 0.589

d. 0.58

e. 27.75

f. 21.64

1.74 **a.** 4.60×10^{-3}

b. 2.208

c. 2.65

d. −13

e. 2

f. 0.81

1.76 **a.** Black rectangle: Area = 124.8 cm^2; perimeter = 44.80 cm

Red rectangle: Area = 48.9 cm^2; perimeter = 45.24 cm

Green rectangle: Area = 8.11 cm^2; perimeter = 11.46 cm

Orange rectangle: Area = 9.0 cm^2; perimeter = 27.80 cm

b. Black rectangle: Area = 0.01248 m^2; perimeter = 0.4480 m

Red rectangle: Area = 0.00489 m^2; perimeter = 0.4524 m

Green rectangle: Area = 0.000811 m^2; perimeter = 0.1146 m

Orange rectangle: Area = 0.00090 m^2; perimeter = 0.2780 m

c. No

1.78 **a.** $\dfrac{0.015\ \text{grain}}{1\ \text{mg}}$

b. $\dfrac{0.0338\ \text{fl oz}}{1\ \text{mL}}$

c. $\dfrac{1\ \text{L}}{1.057\ \text{qt}}$

d. $\dfrac{1\ \text{m}}{1.094\ \text{yd}}$

1.80 1.5 fl oz

1.82 1.4 mL

1.84 290 minutes

1.86 1.31 g/L

1.88 \$25.73/\$467.80 × 100 = 5.500%

1.90 71%

1.92 IgG = 75.09%; IgA = 16.23%; IgM = 7.58%; IgD = 1.10%; IgE = 0.008%

1.94 **a.** 0.792 g/mL

b. 1.03 g/mL

c. 1.98 g/L

d. 8.90 g/cm^3

1.96 Volume = 63.0 cm^3; density = 11.4 g/cm^3

1.98 2.86 mL

1.100 **a.** 4.5×10^6 mm

b. 6.0×10^3 g

c. 9.86×10^{12} km

d. 1.91×10^2 mg

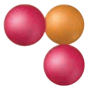
e. 5.0×10^{-6} mg

1.102 54 days

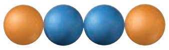
1.104 9.5×10^2 mg

Chapter 2

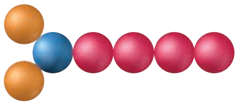
2.2 **a.**



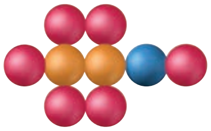
b.



c.



d.



2.4 **a.** H_2O

b. H_2O_2

c. H_2SO_4

d. C_2H_6O

2.6 **a.** One sulfur (S), two oxygen (O)

b. Four carbon (C), ten hydrogen (H)

c. One hydrogen (H), one chlorine (Cl), two oxygen (O)

d. One boron (B), three fluorine (F)

2.8 **a.** The two hydrogen atoms should be denoted by a subscript: H_2S

b. The letter L of chlorine should be lowercase: $HClO_2$

c. The coefficient 2 should not be used to indicate the number of atoms in the molecule. Subscripts should be used instead: H_2N_4

d. The numbers in the formula should be written as subscripts: C_2H_6

2.10 **a.** Charge = 4+; mass = 9 u

b. Charge = 9+; mass = 19 u

c. Charge = 20+; mass = 43 u

d. Charge = 47+; mass = 107 u

2.12 **a.** 4

b. 9

c. 20

d. 47

2.14 **a.** 14 electrons, 14 protons

b. 50 electrons, 50 protons

c. 74 electrons, 74 protons

2.16 **a.** 16 protons, 18 neutrons, 16 electrons

b. 40 protons, 51 neutrons, 40 electrons

c. 54 protons, 77 neutrons, 54 electrons

2.18 **a.** ${}^{28}_{14}\text{Si}$

b. ${}^{40}_{18}\text{Ar}$

c. ${}^{88}_{38}\text{Sr}$

2.20 **a.** Atomic number = 4; mass number = 9; ${}^{9}_{4}\text{Be}$

b. Atomic number = 9; mass number = 19; ${}^{19}_{9}\text{F}$

c. Atomic number = 20; mass number = 43; ${}^{43}_{20}\text{Ca}$

d. Atomic number = 47; mass number = 107; ${}^{107}_{47}\text{Ag}$

2.22 **a.** ${}^{37}_{17}\text{Cl}$

b. ${}^{65}_{29}\text{Cu}$

c. ${}^{66}_{30}\text{Zn}$

2.24 Atomic weights rounded to nearest whole number give He = 4 u and C = 12 u. Three He total 12 u, which will balance one C, which also totals 12 u.

2.26 Ca, calcium

2.28 N, nitrogen

2.30 **a.** 100.1 u

b. 169.9 u

c. 120.4 u

d. 183.4 u

2.32 Ethylene, C_2H_4

2.34 $y = 3$

2.36 **a.** 14 neutrons

b. 27.0 u

2.38 Calculated value = 10.81 u

Periodic table value = 10.81 u

2.40 Calculated value = 63.55 u

Periodic table value = 63.55 u

2.42 1.90 g F

2.44 **a.** 1 mol P atoms = 6.02×10^{23} P atoms

6.02×10^{23} P atoms = 30.97 g P

1 mol P atoms = 30.97 g P

b. 1 mol Al atoms = 6.02×10^{23} Al atoms

6.02×10^{23} Al atoms = 26.98 g Al

1 mol Al atoms = 26.98 g Al

c. 1 mol Kr atoms = 6.02×10^{23} Kr atoms

6.02×10^{23} Kr atoms = 83.80 g Kr

1 mol Kr atoms = 83.80 g Kr

2.46 **a.** 6.14×10^{-23} g

b. 44.5 g

c. 20.95 g

2.48 Molecular weight BF_3 = 67.8 u

Molecular weight H_2S = 34.1 u

0.68 g BF_3

2.50 **a.**
1. 2 C_2H_6O molecules contain 4 C atoms, 12 H atoms, and 2 O atoms.
2. 10 C_2H_6O molecules contain 20 C atoms, 60 H atoms, and 10 O atoms.
3. 100 C_2H_6O molecules contain 200 C atoms, 600 H atoms, and 100 O atoms.
4. 6.02×10^{23} C_2H_6O molecules contain 12.04×10^{23} C atoms, 36.12×10^{23} H atoms, and 6.02×10^{23} O atoms.
5. 1 mol C_2H_6O molecules contains 2 mol C atoms, 6 mol H atoms, and 1 mol O atoms.
6. 46.0 g of C_2H_6O contain 24.0 g of C, 6.0 g of H and 16.0 g of O.

b.
1. 2 $C_4H_{10}O$ molecules contain 8 C atoms, 20 H atoms, and 2 O atoms.
2. 10 $C_4H_{10}O$ molecules contain 40 C atoms, 100 H atoms, and 10 O atoms.
3. 100 $C_4H_{10}O$ molecules contain 400 C atoms, 1000 H atoms, and 100 O atoms.
4. 6.02×10^{23} $C_4H_{10}O$ molecules contain 24.08×10^{23} C atoms, 60.20×10^{23} H atoms, and 6.02×10^{23} O atoms.
5. 1 mol $C_4H_{10}O$ contain 2 4 mol C atoms, 10 mol H atoms, and 1 mol O atoms.
6. 74.0 g of $C_4H_{10}O$ contain 48.0 g of C, 10.0 g of H, and 16.0 g of O.

c.
1. 2 $C_2HBrClF_3$ molecules contain 4 C atoms, 2 H atoms, 2 Br atoms, 2 Cl atoms, and 6 F atoms.
2. 10 $C_2HBrClF_3$ molecules contain 20 C atoms, 10 H atoms, 10 Br atoms, 10 Cl atoms, and 30 F atoms.
3. 100 $C_2HBrClF_3$ molecules contain 200 C atoms, 100 H atoms, 100 Br atoms, 100 Cl atoms, and 300 F atoms.
4. 6.02×10^{23} $C_2HBrClF_3$ molecules contain 12.04×10^{23} C atoms, 6.02×10^{23} H atoms, 6.02×10^{23} Br atoms, 6.02×10^{23} Cl atoms, and 18.06×10^{23} F atoms.
5. 1 mol $C_2HBrClF_3$ molecules contain 2 2 mol C atoms, 1 mol H atoms, 1 mol Br atoms, 1 mol Cl atoms, and 3 mol F atoms.
6. 197.4 g of $C_2HBrClF_3$ contain 24.0 g of C, 1.0 g of H, 79.9 g of Br, 35.5 g of Cl, and 57.0 g of F.

2.52 **a.** 3.01×10^{23} C atoms

b. 5.0 mol H atoms

c. 2.0 g of H

2.54 1.84 mol Fe

2.56 In CH_4, mass % H = 25.3%.

In C_2H_6, mass % H = 20.1%.

2.58 Statements 4–6 are:

4. 6.02×10^{23} $C_6H_{12}O_6$ molecules contain 36.1×10^{23} C atoms, 72.2×10^{23} H atoms, and 36.1×10^{23} O atoms.

5. 1 mol of $C_6H_{12}O_6$ molecules contains 6 mol of C atoms, 12 mol of H atoms, and 6 mol of O atoms.

6. 180.16 g of $C_6H_{12}O_6$ contain 72.06 g of C, 12.10 g of H, and 96.00 g of O.

a. 23.18 g of O

b. 18.0 mol of H atoms

c. 4.50×10^{23} C atoms

2.60 1.17 g

2.62 U-238 would have a greater density because each U-238 nucleus would contain 3 more neutrons than a U-235 nucleus and thus have a greater mass. However, the size (volume) of each atom (measured from the nucleus to the outer electrons) would be the same, so one cm^3 of each isotope would contain the same number of atoms.

2.64 2.32×10^{-23} g

2.66 The density would increase tremendously because many more of the smaller atoms (measured from the nucleus to the outer electrons) would fit into a cm^3. Each of the smaller atoms would have the same mass as the larger atoms, so the density (mass/volume) would be much greater.

Chapter 3

3.2 **a.** Group VIIIB (9), period 4
b. Group IVA (14), period 6
c. Group VA (15), period 4
d. Group IIA (2), period 6

3.4 **a.** Kr, krypton
b. Sn, tin
c. Mo, molybdenum
d. Nd, neodymium

3.6 **a.** 4
b. 10
c. 18

3.8 **a.** Period
b. Period
c. Group
d. Group

3.10 Protons

3.12 **a.** 2
b. 6
c. 8

3.14 Four orbitals; one 2*s*, and three 2*p*.

3.16 Seven orbitals in the subshell can contain a maximum of 14 electrons.

3.18 **a.** 8
b. 5
c. 4
d. 4

3.20 Cesium, Cs, has chemical properties most like sodium, Na. Both elements have one valence-shell electron.

3.22 An ore deposit that contained copper might also be expected to contain gold and silver because all three elements belong to group IB (11) of the periodic table and thus have similar chemical properties.

3.24 **a.** $1s^22s^22p^63s^23p^64s^23d^{10}4p^65s^1$; one electron is unpaired.
b. $1s^22s^22p^63s^23p^2$; two electrons are unpaired.
c. $1s^22s^22p^63s^23p^64s^23d^2$; two electrons are unpaired.
d. $1s^22s^22p^63s^23p^6$; no electrons are unpaired.

3.26 **a.** $1s^22s^22p^63s^2$; six *s* electrons.
b. $1s^22s^22p^3$; three unpaired electrons.
c. $1s^22s^22p^63s^23p^1$; four subshells are filled.

3.28 **a.** C, carbon
b. Na, sodium
c. Si, silicon, and S, sulfur
d. Nb, niobium
e. V, vanadium, and Co, cobalt

3.30 **a.** $[Ar]4s^23d^{10}4p^3$
b. $[Ar]4s^23d^5$
c. $[Ne]3s^23p^2$
d. $[Kr]5s^24d^{10}5p^5$

3.32 Na: $[Ne]3s^1$
Mg: $[Ne]3s^2$
Al: $[Ne]3s^23p^1$
Si: $[Ne]3s^23p^2$
P: $[Ne]3s^23p^3$
S: $[Ne]3s^23p^4$
Cl: $[Ne]3s^23p^5$
Ar: $[Ne]3s^23p^6$

3.34 **a.** *p* area
b. *d* area
c. *f* area
d. *s* area

3.36 **a.** Transition
b. Representative
c. Inner-transition
d. Noble gases
e. Representative

3.38 **a.** Nonmetal
b. Metal
c. Metalloid
d. Metalloid
e. Metal

3.40 **a.** K
b. Bi
c. Sr
d. Sn

3.42 **a.** Ga
b. Sb
c. C
d. Te

3.44 **a.** K
b. Sn
c. Mg
d. Li

3.46 The chemical properties would be the same because chemical properties depend on the number of valence electrons in the atom. The number of valence electrons in isotopes of the same element is identical.

3.48 8.0 mg

3.50 The element has an atomic weight of 40.0, and so is calcium (Ca). It is a representative element and will conduct electricity because it is a metal.

Chapter 4

4.2 a. $:\overset{..}{\underset{..}{\mathrm{I}}}\cdot$
b. $\dot{\mathrm{Sr}}\cdot$
c. $\cdot\overset{\cdot}{\underset{\cdot}{\mathrm{Sn}}}\cdot$
d. $:\overset{..}{\underset{\cdot}{\mathrm{S}}}\cdot$

4.4 **a.** [Kr] $5s^24d^{10}5p^2$
b. [Xe] $6s^1$
c. [Kr] $5s^24d^{10}5p^1$
d. [Kr] $5s^2$

4.6 **a.** $\cdot\overset{\cdot}{\underset{\cdot}{\mathrm{Sn}}}\cdot$
b. $\mathrm{Cs}\cdot$
c. $\overset{\cdot}{\underset{\cdot}{\mathrm{In}}}\cdot$
d. $\dot{\mathrm{Sr}}\cdot$

4.8 a. $\dot{\mathrm{E}}\cdot$
b. $\cdot\overset{\cdot}{\underset{\cdot}{\mathrm{E}}}:$

4.10 **a.** Add 4 or lose 14
b. Add 31 or lose 1
c. Add 5 or lose 13
d. Add 16 or lose 2

4.12 **a.** Lose 1: $\mathrm{Cs} \rightarrow \mathrm{Cs}^+ + e^-$
b. Add 2: $\mathrm{O} + 2e^- \rightarrow \mathrm{O}^{2-}$
c. Add 3: $\mathrm{N} + 3e^- \rightarrow \mathrm{N}^{3-}$
d. Add 1: $\mathrm{I} + e^- \rightarrow \mathrm{I}^-$

4.14 **a.** Se^{2-}
b. Rb^{1+}
c. Al^{3+}

4.16 **a.** Sulfur, S
b. Aluminum, Al
c. Sodium, Na
d. Chlorine, Cl

4.18 **a.** Helium, He
b. Xenon, Xe
c. Argon, Ar
d. Krypton, Kr

4.20 **a.** $\mathrm{Ca} \rightarrow \mathrm{Ca}^{2+} + 2e^-$; $\mathrm{Cl} + e^- \rightarrow \mathrm{Cl}^-$
Formula is CaCl_2.

b. $\mathrm{Li} \rightarrow \mathrm{Li}^+ + e^-$; $\mathrm{Br} + e^- \rightarrow \mathrm{Br}^-$
Formula is LiBr.

c. $\mathrm{Mg} \rightarrow \mathrm{Mg}^{2+} + 2e^-$; $\mathrm{S} + 2e^- \rightarrow \mathrm{S}^{2-}$
Formula is MgS.

4.22 **a.** BaSe
b. $\mathrm{Ba}_3\mathrm{P}_2$
c. BaI_2
d. $\mathrm{Ba}_3\mathrm{As}_2$

4.24 **a.** Binary
b. Binary
c. Not binary
d. Binary
e. Not binary

4.26 **a.** Lithium ion
b. Magnesium ion
c. Barium ion
d. Cesium ion

4.28 **a.** Bromide ion
b. Oxide ion
c. Phosphide ion
d. Fluoride ion

4.30 **a.** Strontium sulfide
b. Calcium fluoride
c. Barium chloride
d. Lithium oxide
e. Magnesium oxide

4.32 **a.** Lead (II) oxide and lead (IV) oxide
b. Copper (I) chloride and copper (II) chloride
c. Gold (I) sulfide and gold (III) sulfide
d. Cobalt (II) oxide and cobalt (III) oxide

4.34 **a.** Plumbous oxide and plumbic oxide
b. Cuprous chloride and cupric chloride
c. Aurous sulfide and auric sulfide
d. Cobaltous oxide and cobaltic oxide

4.36 **a.** $\mathrm{Hg}_2\mathrm{O}$
b. PbO
c. PtI_4
d. $\mathrm{Cu}_3\mathrm{N}$
e. CoS

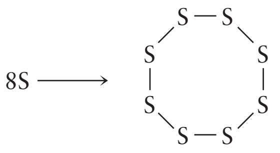
4.38 **a.** 102.9 u
b. 78.1 u
c. 159.2 u
d. 34.8 u

4.40 **a.** Na^+ and Br^-
b. Ca^{2+} and F^-
c. Cu^+ and S^{2-}
d. Li^+ and N^{3-}

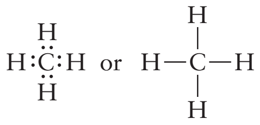
4.42 **a.** 22.99 g of Na^+ and 79.90 g of Br^-
b. 40.08 g of Ca^{2+} and 38.00 g of F^-
c. 127.10 g of Cu^+ and 32.06 g of S^{2-}
d. 20.82 g of Li^+ and 14.01 g of N^{3-}

4.44 **a.** 6.02×10^{23} Na^+ ions and 6.02×10^{23} Br^- ions
b. 6.02×10^{23} Ca^{2+} ions and 12.04×10^{23} F^- ions
c. 12.04×10^{23} Cu^+ ions and 6.02×10^{23} S^{2-} ions
d. 18.06×10^{23} Li^+ ions and 6.02×10^{23} N^{3-} ions

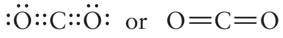
4.46



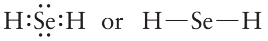
4.48

a. 

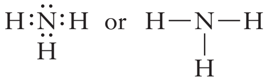
$H:\overset{H}{\underset{H}{C}}:H$ or $H-\overset{H}{\underset{H}{C}}-H$

b. 

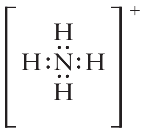
$:\ddot{O}::C::\ddot{O}:$ or $O=C=O$

c. 

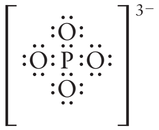
$H:\ddot{Se}:H$ or $H-Se-H$

d. 

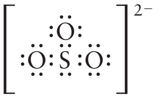
$H:\ddot{N}:H$ or $H-\underset{H}{N}-H$

4.50 a. 

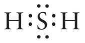
$\left[H:\overset{H}{\underset{H}{N}}:H\right]^{+}$

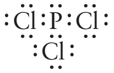
b. 

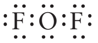
$\left[:\ddot{O}:\overset{:\ddot{O}:}{\underset{:\ddot{O}:}{P}}:\ddot{O}:\right]^{3-}$

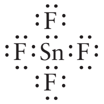
c. 

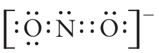
$\left[:\ddot{O}:\overset{:\ddot{O}:}{S}:\ddot{O}:\right]^{2-}$

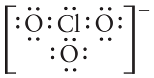
4.52 a.  $H:\ddot{S}:H$ Bent

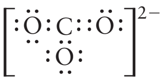
b.  $:\ddot{Cl}:\ddot{P}:\ddot{Cl}:$ with $:\ddot{Cl}:$ below P — Triangular pyramid with P at the top

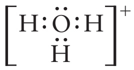
c.  $:\ddot{F}:\ddot{O}:\ddot{F}:$ Bent

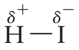
d.  $:\ddot{F}:\overset{:\ddot{F}:}{\underset{:\ddot{F}:}{Sn}}:\ddot{F}:$ Tetrahedral with Sn in center

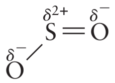
4.54 a.  $[:\ddot{O}:\ddot{N}::\ddot{O}:]^{-}$ Bent

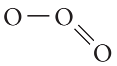
b.  $\left[:\ddot{O}:\underset{:\ddot{O}:}{\ddot{Cl}}:\ddot{O}:\right]^{-}$ Triangular pyramid with Cl at the top

c.  $\left[:\ddot{O}:\underset{:\ddot{O}:}{C}::\ddot{O}:\right]^{2-}$ Flat triangle with C in the center

d.  $\left[H:\underset{H}{\ddot{O}}:H\right]^{+}$ Triangular pyramid with O at the top

4.56 a.  $\overset{\delta+}{H}-\overset{\delta-}{I}$

b.  $\overset{\delta-}{O}-\overset{\delta2+}{S}=\overset{\delta-}{O}$

c. Nonpolarized  $O-O=O$

4.58 a. Polar covalent

b. Polar covalent

c. Nonpolar covalent

d. Polar covalent

e. Ionic

4.60 a. Polar

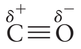
b. Polar

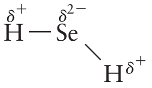
c. Nonpolar

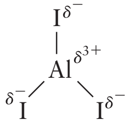
4.62 a. Polar covalent

b. Polar covalent

c. Nonpolar covalent

4.64 a. Polar  $\overset{\delta+}{C}\equiv\overset{\delta-}{O}$

b. Polar  $\overset{\delta+}{H}-\overset{\delta2-}{Se}-H^{\delta+}$

c. Nonpolar  $Al^{\delta3+}$ bonded to three $I^{\delta-}$

4.66 a. Phosphorus trichloride

b. Dinitrogen monoxide

c. Carbon tetrachloride

d. Boron trifluoride

e. Carbon disulfide

4.68 a. ClO_2

b. N_2O

c. SO_2

d. CCl_4

4.70 a. $Ca(ClO)_2$, calcium hypochlorite

b. $CsNO_2$, cesium nitrite

c. $MgSO_3$, magnesium sulfite

d. $K_2Cr_2O_7$, potassium dichromate

4.72 a. $MgSO_3$

b. $Ra(OH)_2$

c. $CaCO_3$

d. $(NH_4)_2\ SO_4$

e. $LiHCO_3$

4.74 a. M_2SO_3

b. $MC_2H_3O_2$

c. MCr_2O_7

d. MPO_4

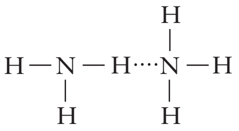
e. $M(NO_3)_3$

4.76 The stronger the attractive forces between molecules, the higher the melting and boiling points. Thus, we can conclude that the forces attracting dimethyl ether molecules to one another are weaker than the forces attracting ethyl alcohol molecules to one another. Because both compounds are covalently bonded, it is likely that the attractive forces are polar forces, and we might conclude that ethyl alcohol is more polar than dimethyl ether.

4.78 The predominant forces that exist between molecules of noble gases are dispersion forces because noble gas molecules are nonpolar. Dispersion forces increase with increasing mass of the particles involved, so the boiling points of the noble gases would increase in the order of He, Ne, Ar, Kr, Xe, and Rn.

4.80 The relatively high melting point indicates that it is unlikely that weak dispersion forces are the predominant forces present. Dipolar forces are also quite weak and therefore are also unlikely to be the forces present.

4.82 NH_3



$$\begin{array}{ccccc} & & & & H \\ & & & & | \\ H- & N & -H\cdots & N & -H \\ & | & & | & \\ & H & & H & \end{array}$$

4.84 8.06 g

4.86 N_2O, covalent, dinitrogen monoxide

4.88 The colors of some compounds result from the presence of water in the compounds. To determine if the presence of water in a compound caused its color, heat the compound in a container, which could capture any gases given off. If the water vapor were the only gas given off and the color changed, then it would be evident that the water produced the original color.

4.90 Potassium dichromate is $K_2Cr_2O_7$. Potassium chromate is K_2CrO_4. Potassium phosphate is K_3PO_4. Potassium permanganate is $KMnO_4$. The colored compounds of potassium ($K_2Cr_2O_7$, K_2CrO_4 and $KMnO_4$) have a transition metal as part of the polyatomic ion.

4.92 A negatively charged ion will be larger than a nonmetal atom of the same element, because as the electrons are added to the atom, the electron cloud will increase in size as the nucleus is not able to hold onto the electrons as well as their number increases.

4.94 CCl_4 molecules are nonpolar because the molecules are symmetrical. If a positively charged object were used in place of the balloon, the water molecules would still be attracted by the object, and the carbon tetrachloride molecules would not be affected by the object.

Chapter 5

5.2

	Reactants	*Products*
a.	H_2, Cl_2	HCl
b.	$KClO_3$	KCl, O_2
c.	magnesium oxide, carbon	magnesium, carbon monoxide
d.	ethane, oxygen	carbon dioxide, water

5.4
- **a.** Not consistent: The number of O atoms is not the same on both sides.
- **b.** Consistent
- **c.** Not consistent: The masses of reactants and products are not equal.
- **d.** Consistent

5.6

	Left side	*Right side*	*Classification*
a.	1Ag, 1Cu, 2N, 6O	1Ag, 1Cu, 1N, 3O	Unbalanced
b.	4N, 8O	4N, 8O	Balanced
c.	1Mg, 2O	2Mg, 2O	Unbalanced
d.	4H, 1S, 6O, 1Ca	4H, 1S, 6O, 1Ca	Balanced

5.8
- **a.** $2KClO_3(s) \rightarrow 2KCl(s) + 3O_2(g)$
- **b.** $2C_2H_6(g) + 7O_2(g) \rightarrow 4CO_2(g) + 6H_2O(\ell)$
- **c.** $2N_2(g) + 5O_2(g) \rightarrow 2N_2O_5(g)$
- **d.** $MgCl_2(s) + H_2O(g) \rightarrow MgO(s) + 2HCl(g)$
- **e.** $CaH_2(s) + 2H_2O(\ell) \rightarrow Ca(OH)_2(s) + 2H_2(g)$
- **f.** $2Al(s) + Fe_2O_3(s) \rightarrow Al_2O_3(s) + 2Fe(s)$
- **g.** $2Al(s) + 3Br_2(g) \rightarrow 2AlBr_3(s)$
- **h.** $Hg_2(NO_3)_2(aq) + 2NaCl(aq) \rightarrow Hg_2Cl_2(s) + 2NaNO_3(aq)$

5.10
- **a.** +1
- **b.** +3
- **c.** 0
- **d.** +1
- **e.** +3
- **f.** +5

5.12
- **a.** Cr (+6)
- **b.** S (+2)
- **c.** N (+5)
- **d.** P (+5)
- **e.** Cl (+7)
- **f.** Cl (+3)

5.14
- **a.** Oxidized
- **b.** Neither
- **c.** Reduced
- **d.** Oxidized
- **e.** Oxidized

5.16

a. $\underset{0}{2Cu(s)} + \underset{0}{O_2(g)} \rightarrow \underset{+2\ \ -2}{2CuO(s)}$

Oxidizing agent: O_2

Reducing agent: Cu

b. $\underset{0}{Cl_2(g)} + \underset{+1\ \ -1}{2KI(aq)} \rightarrow \underset{+1\ \ -1}{2KCl(aq)} + \underset{0}{I_2(aq)}$

Oxidizing agent: Cl_2

Reducing agent: KI (I)

c. $\underset{+4\ \ -2}{3MnO_2(s)} + \underset{0}{4Al(s)} \rightarrow \underset{+3\ \ -2}{2Al_2O_3(s)} + \underset{0}{3Mn(s)}$

Oxidizing agent: MnO_2 (Mn)

Reducing agent: Al

d. $\underset{+1}{2H^+(aq)} + \underset{+4\ \ -2}{3SO_3^{2-}(aq)} + \underset{+5\ \ -2}{2NO_3^-(aq)} \rightarrow \underset{+2\ \ -2}{2NO(g)} + \underset{+1\ \ -2}{H_2O(\ell)} + \underset{+6\ \ -2}{3SO_4^{2-}(aq)}$

Oxidizing agent: NO_3^- (N)

Reducing agent: SO_3^{2-} (S)

e. $\underset{0}{Mg}(s) + 2\underset{+1}{H}\underset{-1}{Cl}(aq) \rightarrow \underset{+2}{Mg}\underset{-1}{Cl_2}(aq) + \underset{0}{H_2}(g)$

Oxidizing agent: HCl (H^+)

Reducing agent: Mg

f. $4\underset{+4}{N}\underset{-2}{O_2}(g) + \underset{0}{O_2}(g) \rightarrow 2\underset{+5}{N_2}\underset{-2}{O_5}(g)$

Oxidizing agent: O_2

Reducing agent: NO_2 (N)

5.18 Oxidizing agent: NaOH (H)

Reducing agent: Al

5.20 **a.** Nonredox, decomposition

b. Redox, single replacement

c. Nonredox, double replacement

d. Nonredox, combination

e. Redox, combination

f. Redox, combination

5.22 Nonredox, decomposition

5.24 Redox

5.26 Redox

5.28 **a.** Li^+, NO_3^-

b. Na^+, HPO_4^{2-}

c. Ca^{2+}, ClO_3^-

d. K^+, OH^-

e. Mg^{2+}, Br^-

f. NH_4^+, SO_4^{2-}

5.30 **a.** Total ionic: $SO_2(aq) + H_2O(\ell) \rightarrow 2H^+(aq) + SO_3^{2-}(aq)$

Spectator ions: none

Net ionic: $SO_2(aq) + H_2O(\ell) \rightarrow 2H^+(aq) + SO_3^{2-}(aq)$

b. Total ionic: $Cu^{2+}(aq) + SO_4^{2-}(aq) + Zn(s) \rightarrow Cu(s) + Zn^{2+}(aq) + SO_4^{2-}(aq)$

Spectator ions: SO_4^{2-}

Net ionic: $Cu^{2+}(aq) + Zn(s) \rightarrow Cu(s) + Zn^{2+}(aq)$

c. Total ionic:

$2K^+(aq) + 2Br^-(aq) + 4H^+(aq) + 2SO_4^{2-}(aq) \rightarrow$

$Br_2(aq) + SO_2(aq) + 2K^+(aq) + SO_4^{2-}(aq) + 2H_2O(\ell)$

Spectator ions: K^+, one SO_4^{2-}

Net ionic: $2Br^-(aq) + 4H^+(aq) + SO_4^{2-}(aq) \rightarrow Br_2(aq) + SO_2(aq) + 2H_2O(\ell)$

d. Total ionic:

$Ag^+(aq) + NO_3^-(aq) + Na^+(aq) + OH^-(aq) \rightarrow AgOH(s) + Na^+(aq) + NO_3^-(aq)$

Spectator ions: Na^+, NO_3^-

Net ionic: $Ag^+(aq) + OH^-(aq) \rightarrow AgOH(s)$

e. Total ionic: $BaCO_3(s) + 2H^+(aq) + 2NO_3^-(aq) \rightarrow Ba^{2+}(aq) + 2NO_3^-(aq) + CO_2(g) + H_2O(\ell)$

Spectator ions: NO_3^-

Net ionic:

$BaCO_3(s) + 2H^+(aq) \rightarrow Ba^{2+}(aq) + CO_2(g) + H_2O(\ell)$

f. Total ionic: $N_2O_5(aq) + H_2O(\ell) \rightarrow 2H^+(aq) + 2NO_3^-(aq)$

Spectator ions: none

Net ionic: $N_2O_5(aq) + H_2O(\ell) \rightarrow 2H^+(aq) + 2NO_3^-(aq)$

5.32 **a.** $H^+(aq) + NO_3^-(aq) + K^+(aq) + OH^-(aq) \rightarrow K^+(aq) + NO_3^-(aq) + H_2O(\ell)$

Spectator ions: K^+, NO_3^-

Net ionic: $H^+(aq) + OH^-(aq) \rightarrow H_2O(\ell)$

b. $3H^+(aq) + PO_4^{3-}(aq) + 3NH_4^+(aq) + 3OH^-(aq) \rightarrow 3NH_4^+(aq) + PO_4^{3-}(aq) + 3H_2O(\ell)$

Spectator ions: NH_4^+, PO_4^{3-}

Net ionic: $3H^+(aq) + 3OH^-(aq) \rightarrow 3H_2O(\ell)$

c. $H^+(aq) + I^-(aq) + Na^+(aq) + OH^-(aq) \rightarrow Na^+(aq) + I^-(aq) + H_2O(\ell)$

Spectator ions: Na^+, I^-

Net ionic: $H^+(aq) + OH^-(aq) \rightarrow H_2O(\ell)$

In every net ionic reaction, H^+ reacts with OH^- to form H_2O

5.34 Exothermic: Heat is a product of the reaction.

5.36 The insulation around the ice slows its rate of melting by preventing it from absorbing heat. However, this prevents the ice from performing its cooling function in the cooler. For the cooler to work properly, heat must move from the warmer food to the cooler ice, where it is absorbed as the ice melts.

5.38 **a.** $S(s) + O_2(g) \rightarrow SO_2(g)$

2. 1 mol S + 1 mol O_2 → 1mol SO_2
3. 6.02×10^{23} S atoms + 6.02×10^{23} O_2 molecules → 6.02×10^{23} SO_2 molecules
4. 32.06 g S + 32.00 g O_2 → 64.06 g SO_2

b. $Sr(s) + 2H_2O(\ell) \rightarrow Sr(OH)_2(s) + H_2(g)$

2. 1 mol Sr + 2 mol H_2O → 1 mol $Sr(OH)_2$ + 1 mol H_2
3. 6.02×10^{23} Sr atoms + 12.04×10^{23} H_2O molecules → 6.02×10^{23} $Sr(OH)_2$ molecules + 6.02×10^{23} H_2 molecules
4. 87.62 g Sr + 36.03 g H_2O → 121.64 g $Sr(OH)_2$ + 2.02 g H_2

c. $2H_2S(g) + 3O_2(g) \rightarrow 2H_2O(g) + 2SO_2(g)$

2. 2 mol H_2S + 3 mol O_2 → 2 mol H_2O + 2 mol SO_2
3. 12.04×10^{23} H_2S molecules + 18.06×10^{23} O_2 molecules → 12.04×10^{23} H_2O molecules + 12.04×10^{23} SO_2 molecules
4. 68.15 g H_2S + 96.00 g O_2 → 36.03 g H_2O + 128.12 g SO_2

d. $4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(g)$

2. 4 mol NH_3 + 5 mol O_2 → 4 mol NO + 6 mol H_2O
3. 24.08×10^{23} NH_3 molecules + 30.10×10^{23} O_2 molecules → 24.08×10^{23} NO molecules + 36.12×10^{23} H_2O molecules
4. 68.14 g NH_3 + 160.00 g O_2 → 120.04 g NO + 108.10 g H_2O

e. $CaO(s) + 3C(s) \rightarrow CaC_2(s) + CO(g)$

2. 1 mol CaO + 3 mol C → 1 mol CaC_2 + 1 mol CO

3. 6.02×10^{23} CaO molecules + 18.06×10^{23} C atoms → 6.02×10^{23} CaC_2 molecules + 6.02×10^{23} CO molecules

4. 56.08 g CaO + 36.03 g C → 64.10 g CaC_2 + 28.01 g CO

5.40 $2SO_2(g) + O_2(g) \rightarrow 2SO_3(g)$

2. 2 mol SO_2 + 1 mol O_2 → 2 mol SO_3

3. 12.0×10^{23} SO_2 molecules + 6.02×10^{23} O_2 molecules → 12.0×10^{23} SO_3 molecules

4. 128 g SO_2 + 32.0 g O_2 → 160 g SO_3

Factors:

$$\frac{12.0 \times 10^{23}\ SO_2\ \text{molecules}}{6.02 \times 10^{23}\ O_2\ \text{molecules}}; \quad \frac{12.0 \times 10^{23}\ SO_3\ \text{molecules}}{12.0 \times 10^{23}\ SO_2\ \text{molecules}};$$

$$\frac{32.0\ g\ O_2}{128\ g\ SO_2}; \quad \frac{128\ g\ SO_2}{160\ g\ SO_3}; \quad \frac{32.0\ g\ O_2}{160\ g\ SO_3}; \quad \frac{128\ g\ SO_2}{32.0\ g\ O_2};$$

$$\frac{2\ mol\ SO_2}{1\ mol\ O_2}; \quad \frac{2\ mol\ SO_3}{2\ mol\ SO_2}; \quad \frac{1\ mol\ O_2}{2\ mol\ SO_3}; \quad \frac{1\ mol\ O_2}{2\ mol\ SO_2}; \quad \frac{2\ mol\ SO_3}{32.0\ g\ O_2};$$

$$\frac{128\ g\ SO_2}{2\ mol\ SO_2}; \quad \frac{2\ mol\ SO_2}{32.0\ g\ O_2}; \quad \frac{2\ mol\ SO_3}{1\ mol\ O_2}; \quad \frac{160\ g\ SO_3}{32.0\ g\ O_2}; \quad \frac{32.0\ g\ O_2}{1\ mol\ O_2}$$

This list does not include all possible factors.

5.42 892 g

5.44 445 g

5.46 495 g

5.48 1.02×10^3 g

5.50 256 g

5.52 **a.** O_2 is the limiting reactant.

b. 71.9 g NO_2

5.54 144 g

5.56 72.96%

5.58 72.5%

5.60 89.0%

5.62 $BaCl_2(aq) + Na_2SO_4(aq) \rightarrow 2NaCl(aq) + BaSO_4(s)$

Net ionic: $Ba^{2+}(aq) + SO_4^{2-}(aq) \rightarrow BaSO_4(s)$

5.64 7.502 g

Chapter 6

6.2 **a.** 121 mL

b. 158 mL

c. 67.9 mL

6.4 2 mL

6.6 **a.** The volume of the balloon will increase so the density will decrease.

b. $\dfrac{1.31\ g}{1\ L}$

6.8 As the ball travels upward and slows, more and more of its kinetic energy is converted into potential energy. At the maximum height, when the ball stops before starting to fall, all the energy is in the form of potential energy. As the ball falls faster and faster, more and more of the potential energy is converted back into kinetic energy. If there were no energy losses from air resistance, the ball would gain back as much kinetic energy as it had when it was initially thrown.

6.10 N_2O kinetic energy $= 3.14 \times 10^{10} \dfrac{g\ cm^2}{s^2}$

Sevoflurane kinetic energy $= 3.13 \times 10^{10} \dfrac{g\ cm^2}{s^2}$

6.12 **a.** Particles (molecules) in a liquid move freely and therefore assume the container shape, but the cohesive forces between the particles prevent them from separating completely from each other and filling the container.

b. There is very little space between the particles (molecules) of liquids and solids. As a result, increased pressure cannot push the particles closer together and will have little influence on their volumes.

c. Gas molecules move around essentially unrestricted, and on average, equal numbers collide with each of the walls of a container in a given amount of time. The collisions cause the pressure on the walls, so the pressure on all the walls is the same.

6.14 Heat must be added to a substance to convert it from the solid to the liquid state, and then from the liquid to the gaseous state. If the added heat causes no temperature difference between the two states, as when a solid melts to a liquid at the melting point, then the added heat increases the potential energy of the particles of the substance. Thus, at the melting point, the particles of both solid and liquid forms of a substance will have the same kinetic energy because they are at the same temperature. However, particles of the liquid will have more potential energy, corresponding to the energy that had to be added to change the solid to a liquid. Similar arguments apply for a comparison of the liquid and gaseous states of a substance.

6.16 **a.** Gaseous

b. Solid

c. Gaseous

d. Gaseous

6.18 **a.** 0.957 atm

b. 727 torr

c. 14.1 psi

d. 0.966 bar

6.20 **a.** 14.3 atm

b. 14.4 bar

c. 1.09×10^4 mmHg

d. 427 in. Hg

6.22 **a.** 4.1 K

b. −258.9°C

c. 336.7 K

6.24 Column A: $P_f = 1.50$ atm; Column B: $V_f = 4.49$ L; Column C: $T_f = 221$ K

6.26 138 mL

6.28 3.7 atm

6.30 31.6 L

6.32 714 L

6.34 4.6 L

6.36 2.5 L

6.38 3.62 mL

6.40 1.4×10^4 ft^3

6.42 1.33 L

6.44 5.00 g/L

6.46 **a.** 0.0130 mol

b. 7.65 atm

c. 8.35 L

6.48 3.19 atm

6.50 26.3 g

6.52 2.7 mol

6.54 168 g/mol

6.56 44.1 g/mol; the gas is most likely CO_2

6.58 $420\text{ torr}\left(\frac{80\%\text{ He}}{20\%\text{ O}_2}\right)$

6.60 O_2 mass/H_2 mass $= 16$ according to Graham's law. From the periodic table, O_2 mass/H_2 mass $= 32\text{ u}/2\text{ u} = 16$. The agreement is very good.

6.62 The helium-filled balloon would appear to go flat first because helium molecules diffuse through the rubber balloon faster than do nitrogen molecules. The rates of diffusion according to Graham's law would be He rate/N_2 rate $= \sqrt{28.0\text{ u}/4.00\text{ u}} = 2.6$. Thus, He would be expected to escape through the balloon 2.6 times as fast as nitrogen.

6.64 **a.** Exothermic

b. Exothermic

c. Endothermic

6.66 Liquid water was heated to become steam (endothermic process), and then the steam was cooled to become liquid water again (exothermic process).

6.68 Liquid methylene chloride evaporates very rapidly, and when it evaporates, it absorbs heat. Thus, the liquid acted to cool and temporarily anesthetize any tissue on which it was sprayed.

6.70 The boiling points of the two liquids are different. Thus, a measurement of the temperature of each boiling liquid would differentiate between them. The ethylene glycol would have the higher boiling point of the two.

6.72 The temperature of boiling water is influenced by the atmospheric pressure on the water. On top of Mount Everest the atmospheric pressure is quite low, so water boils at a temperature significantly lower than the normal boiling point of 100°C. The temperature of the burning campfire would not be influenced by the altitude. Thus, the potato would cook faster if it were put into the campfire.

6.74 Since sand does not sublime, heat the mixture and let the hot iodine vapor out of the hot chamber and to a cool surface. The pure iodine vapor will condense to a solid on the cool surface, and can be scraped off and collected.

6.76 **a.** 3.6×10^2 cal

b. 7×10^3 cal

c. 2.4×10^3 cal

6.78 **a.** 4.07×10^7 cal

b. 7.07×10^7 cal

c. 5.71×10^7 cal

6.80 7.72×10^4 cal

6.82 1.96×10^{-3} g/mL

6.84 1.16 L The reaction is a redox combination reaction.

6.86 The air of the atmosphere contains about 21 volume percent oxygen at any altitude. However, the pressure of the atmosphere at high altitudes is less than the pressure at lower altitudes. If the air at a higher altitude is at the same temperature as at a lower altitude, and since $P = nRT/V$, the same volume (V) of a lung full of air at a higher altitude and lower pressure (P) contains fewer moles of gas (n), and so fewer moles of oxygen. So, from the point of view of the number of molecules of oxygen, the higher altitude air has less oxygen, but from a percentage point of view it still contains 21% oxygen.

Chapter 7

7.2 **a.** Solvent: water; solute: sodium hypochlorite

b. Solvent: isopropyl alcohol; solute: water

c. Solvent: water; solute: hydrogen peroxide

d. Solvent: SD alcohol; solutes: water, glycerin, fragrance, menthol, benzophenone, coloring

7.4 **a.** Not a solution because it is not homogeneous. It is cloudy rather than clear.

b. Solution; solvent: water; solutes: all dissolved components.

c. Not a solution because it is not homogeneous. Bits of pulp can be seen.

d. Solution if prepared carefully with a tea bag or good strainer; solvent: water; solutes: all dissolved components.

e. Not a solution because it is not homogeneous.

7.6 **a.** The oil and vinegar are immiscible.

b. The alcohol is soluble in the water.

c. The tar is soluble in the chloroform.

7.8 **a.** Unsaturated

b. Supersaturated

c. Saturated

7.10 The solution could be carefully cooled to a temperature lower than room temperature. Another method would be to allow some of the solvent to evaporate.

7.12 **a.** Soluble

b. Insoluble

c. Slightly soluble

d. Very soluble

e. Slightly soluble

7.14 According to Table 7.4, barium sulfate is insoluble in water; therefore it cannot form a solution. In a suspension, the solid particles are noncolloidally dispersed in the water.

7.16 **a.** Soluble in benzene
- **b.** Soluble in benzene
- **c.** Soluble in water
- **d.** Soluble in benzene

7.18 Insoluble. The structure indicates that halothane is a nonpolar material. Therefore, halothane would not be soluble in a polar solvent, such as water.

7.20 **a.** 0.364 M
- **b.** 0.860 M
- **c.** 1.75 M

7.22 **a.** 0.500 M
- **b.** 0.200 M
- **c.** 0.26 M

7.24 **a.** 0.376 mol
- **b.** 0.0750 mol
- **c.** 571 mL

7.26 **a.** 0.820 g
- **b.** 0.130 L
- **c.** 0.516 L

7.28 **a.** 5.0%
- **b.** 5.0%
- **c.** 5.0%

7.30 **a.** 7.41%
- **b.** 15.3%
- **c.** 54.5%
- **d.** 44.1%

7.32 **a.** 11.1%
- **b.** 10.7%
- **c.** 7.48%

7.34 **a.** 7.5%
- **b.** 7.5%
- **c.** 3.0%
- **d.** 43.0%

7.36 0.025 L or 25 mL

7.38 **a.** 5.00% (w/v) dextrose
- **b.** 5.00% (w/v)
- **c.** 0.900% (w/v) saline

7.40 About 40%

7.42 **a.** Put 0.0300 mol (4.26 g) of solid Na_2SO_4 into a 200 mL volumetric flask and add enough pure water to fill the flask to the mark after the solid dissolves.
- **b.** Put 0.0625 mol (11.8 g) of solid $Zn(NO_3)_2$ into a 250 mL volumetric flask and add enough pure water to fill the flask to the mark after the solid dissolves.
- **c.** Mix together 3.38 g of solid NaCl and 147 g (147 mL) of pure water. Allow the NaCl to dissolve.
- **d.** Put 0.94 g of solid KCl into a 125 mL volumetric flask and add enough pure water to fill the flask to the mark after the solid dissolves.

7.44 2.3 g NaCl

7.46 **a.** 32.3 g
- **b.** 0.700 mol
- **c.** 31.3 mL
- **d.** 2.10 g

7.48 **a.** Add 1.67 L of 18.0 M H_2SO_4 solution to enough water to give 5.00 L of solution. The 18.0 M acid should be added to water, and not the water to the acid. One way to make the desired solution is to add the 1.67 L of 18.0 M acid to about 3 L of pure water. Stir the resulting solution, then add enough additional water to bring the total volume to 5.00 L.
- **b.** Put 41.7 mL of 3.00 M $CaCl_2$ solution into a 250 mL volumetric flask and add enough pure water to fill the flask to the mark when the contents are well mixed.
- **c.** Put 30.0 mL of a 10.0% solution into a calibrated volumetric container (such as a volumetric flask or large volumetric cylinder) and add enough pure water to bring the total volume of well-mixed solution to 200 mL.
- **d.** Put 100 mL of a 50.0% solution into a calibrated volumetric container and add enough pure water to bring the total volume of well-mixed solution to 500 mL.

7.50 **a.** 0.00650 M
- **b.** 0.0488 M
- **c.** 0.0195 M
- **d.** 0.0139 M

7.52 16.6 g

7.54 20.0 mL

7.56 50.7 mL

7.58 42.3 mL

7.60 1.3 g

7.62 Because ice cream is essentially a solution of substances dissolved in water, the freezing point of the solution is lower than that of pure water. The temperature of a mixture of ice and pure water is the same as the freezing point of pure water. Thus, a mixture of ice and water has a temperature higher than the freezing point of the ice cream solution. A mixture of ice, salt, and water has a temperature (freezing point) lower than that of pure water. If enough salt is added to the ice and water mixture, the temperature can be made lower than the freezing point of the ice cream solution, and it will freeze.

7.64 **a.** Boiling point = 101.6°C; freezing point = −5.58°C
- **b.** Boiling point = 100.78°C; freezing point = −2.79°C
- **c.** Boiling point = 102.3°C; freezing point = −8.37°C
- **d.** Boiling point = 103.1°C; freezing point = −11.2°C

7.66 **a.** Boiling point = 100.26°C; freezing point = 20.93°C
- **b.** Boiling point = 100.39°C; freezing point = 21.40°C
- **c.** Boiling point = 103.35°C; freezing point = 212.0°C

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

7.68 **a.** Osmolarity = 0.15

b. Osmolarity = 0.45

c. Osmolarity = 1.19

7.70 $\pi = 4.65 \times 10^3$ torr $= 4.65 \times 10^3$ mmHg = 6.12 atm

7.72 $\pi = 1.12 \times 10^4$ torr $= 1.12 \times 10^4$ mmHg = 14.7 atm

7.74 $\pi = 5.88 \times 10^4$ torr $= 5.88 \times 10^4$ mmHg = 77.4 atm

7.76 $\pi = 3.5 \times 10^3$ torr $= 3.5 \times 10^3$ mmHg = 4.6 atm

7.78 $\pi = 9.95 \times 10^3$ torr $= 9.95 \times 10^3$ mmHg = 13.1 atm

7.80 Water will flow from the 5.00% solution into the 10.0% solution. The 10.0% solution will become diluted as osmosis takes place.

7.82 Much of the soiling material to be removed by washing consists of fats and oils, which are nonpolar and will not dissolve in water. The soaps or detergents act as emulsifying agents, which allow the nonpolar materials to be suspended in water and removed from the material being washed.

7.84 **a.** Na^+ and Cl^-

b. Urea molecules

c. K^+, Cl^- and glucose molecules

7.86 1.07 g/mL

7.88 10.2 mL

Chapter 8

8.2 **a.** Nonspontaneous: The rocket engines of the shuttle must operate continuously to push the shuttle into an orbit.

b. Spontaneous: Once ignited, the fuel continues to burn without additional input of energy.

c. Nonspontaneous: Heat must be supplied continuously to keep the water boiling.

d. Nonspontaneous: The only way to raise the temperature of a substance is to supply heat.

e. Nonspontaneous: To make your room orderly, someone must provide some work to move the clothing, etc., around. The work done represents an input of energy to the room.

8.4 **a.** Exergonic: The person doing the pushing is giving up energy to the automobile.

b. Endergonic: The ice must gain energy in the form of heat in order to melt.

c. Exergonic: The surroundings lose heat to the ice in order for the ice to melt.

d. Exergonic: In order to condense, the steam must give up some energy in the form of heat.

e. Endergonic: The heat given up by the steam as it condenses is accepted by the surroundings.

8.6 **a.** Both the energy and the entropy of the water decrease when water freezes. The process is spontaneous if the temperature of the surroundings is lower than 0°C.

b. The energy of the water decreases while the entropy stays essentially constant. The process is spontaneous.

c. The energy of the perfume increases slightly as energy is absorbed during evaporation. The entropy of the perfume increases a great deal as the molecules evaporate from the liquid and disperse throughout the room. The process is spontaneous.

8.8 **a.** Entropy is highest at the end of the play because the players are in a more mixed-up state as compared to just before the play began.

b. The answer is the 10% copper/gold alloy or the 2% alloy, depending on the atoms discussed. A lower concentration of copper atoms allows more disorder among the copper atoms, but more order among the gold atoms. A higher concentration of copper allows less disorder for the copper atoms, but increases the disorder of the gold atoms.

c. Entropy is highest with the purse on the ground and the contents scattered.

d. The mixture characteristic of coins in a piggy bank would have the highest entropy of the choices.

e. The mixture of loose pearls in a box would have the highest entropy of the choices.

8.10 The answers are subjective and depend on the meaning given to the terms *very slow*, *slow*, and *fast*.

a. Very slow

b. Slow

c. Very slow

d. Slow

e. Fast

8.12 **a.** Any of the following could be measured at different times: the weight of the block, the weight or volume of the water produced by the melting block, and the physical dimensions of the melting block.

b. Either of the following could be measured at different times: the distance a weighted object penetrates into a sample, and the force required to break a specific-sized piece.

c. Either of the following could be measured at different times: the length of the unburned candle and the weight of the candle.

8.14 **a.** Rate = 0.0330 M/min

b. Rate = 0.0194 M/min

8.16 Rate $= 3.96 \times 10^{-3}$ M/min

8.18 5.66×10^{-4} moles N_2. Rate $= 1.51 \times 10^{-6}$ M/sec

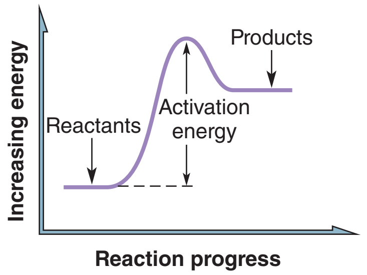
8.20 **a.** Assumption 1 is being violated. According to assumption 1, decreasing the concentrations of reactants would decrease the number of collisions and so decrease the rate at which the molecules would react.

b. Assumption 2 is being violated. According to assumption 2, molecules must collide with a certain minimum energy in order to react. At a lower temperature, fewer molecules would have the necessary minimum energy, so the reaction should go slower, not faster.

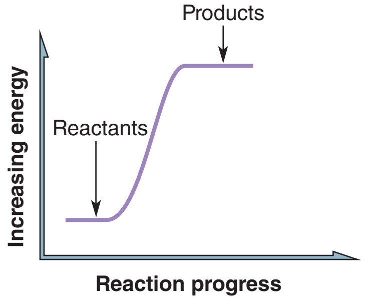
c. Assumption 1 is being violated. According to assumption 1, increasing the concentration of either of the reactants should increase the number of collisions and so increase the rate of the reaction.

8.22 An increase in temperature increases the speeds of the molecules involved in a reaction. The increased speed acts to increase the reaction rate in two ways. First, it causes more collisions to occur between molecules in a given amount of time. Second, it causes the energy of the colliding molecules to be greater so that more of the collisions will involve molecules that have at least the minimum energy needed for a reaction to take place.

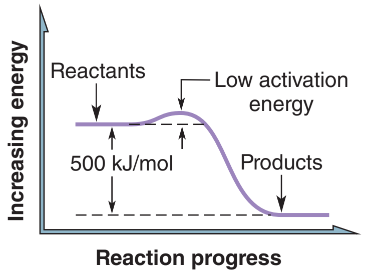
8.24 **a.**


Products
Reactants
Activation energy
Increasing energy
Reaction progress

b.

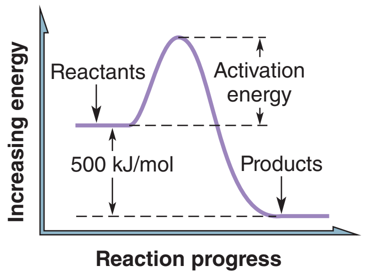

Products
Reactants
Increasing energy
Reaction progress

8.26 **a.**


Reactants
Low activation energy
500 kJ/mol
Products
Increasing energy
Reaction progress

AT ROOM TEMP.

b.


Reactants
Activation energy
500 kJ/mol
Products
Increasing energy
Reaction progress

AT 150° C

Both reactions are exothermic and the products have 500 kJ/mol less energy than the reactants, so both reactions give up 500 kJ/mol. The reaction that takes place at room temperature has a smaller activation energy than the reaction that must be heated to 150°C.

8.28 **a.** Slow to rapid, depending on the state of division of the solid. If large lumps of CaO were exposed to gaseous HCl, the reaction would be slow, since only the CaO on the surface of the lumps would be available. If the CaO were divided into dust-size particles and blown into the gaseous HCl, the reaction would go quite rapidly.

b. Slow. This reaction involves only solids, so only the material at the surface where two solid particles come into contact can react. As in part a, dividing the solids into a fine powder before mixing would speed the reaction significantly.

c. Won't react. The particles of both reactants carry a negative electrical charge, so the particles will repel each other, and collisions between them are highly unlikely.

d. Rapid. The particles of both reactants are in solution, where collisions occur frequently. Also, even though one of the particles is electrically charged, the other is not, so the charge will not diminish or enhance the chances for collisions between reactants.

8.30 Heat the reaction mixture, add a catalyst, or increase the concentration of one or more of the reactants.

8.32 About 0.93 hours or 56 minutes

8.34 Catalysts provide reaction pathways with lower activation energy. They may do this by reacting to form an intermediate structure that yields products when it breaks up or by providing a surface on which the reactants react.

8.36 **a.** Equilibrium would be indicated when the intensity of the violet color of the reaction mixture remained constant with time.

b. Equilibrium would be indicated when the amount of undissolved sugar remained constant with time.

c. Equilibrium would be indicated when either the intensity of the red-brown color of the reaction mixture remained constant with time or the total pressure of the reaction mixture remained constant with time.

8.38 The concentrations of H_2 and Br_2 would decrease, and the concentration of HBr would increase. The intensity of the red-brown color of the mixture would stop decreasing and would become constant when equilibrium was established.

8.40 **a.** $K = \dfrac{[CO_2]^2}{[CO]^2[O_2]}$

b. $K = \dfrac{[NO_2]^2}{[N_2O_4]}$

c. $K = \dfrac{[CO_2]^4[H_2O]^6}{[C_2H_6]^2[O_2]^7}$

d. $K = \dfrac{[NO]^2[Cl_2]}{[NOCl]^2}$

e. $K = \dfrac{[O_2][ClO_2]^4}{[Cl_2O_5]^2}$

8.42 **a.** $K = \dfrac{[Fe(CN)_6{}^{3-}]}{[Fe^{3+}][CN^-]^6}$

b. $K = \dfrac{[Ag(NH_3)_2{}^+]}{[Ag^+][NH_3]^2}$

c. $K = \dfrac{[AuCl_4{}^-]}{[Au^{3+}][Cl^-]^4}$

8.44 **a.** $CH_4 + 2O_2 \rightleftarrows CO_2 + 2H_2O$

b. $3H_2 + CO \rightleftarrows CH_4 + H_2O$

c. $2O_3 \rightleftarrows 3O_2$

d. $4NO_2 + 6H_2O \rightleftarrows 4NH_3 + 7O_2$

8.46 K = 0.47

8.48 K = 0.099

8.50 **a.** The concentration of products will be larger than the concentration of reactants.

b. The concentration of products will be larger than the concentration of reactants.

c. The concentration of products will be smaller than the concentration of reactants.

d. The concentration of products will be smaller than the concentration of reactants.

8.52 **a.** Shift left

b. Shift right

c. Shift left

8.54 **a.** Shift right: The color will become less blue and more purple.

b. Shift right: The amount of solid $PbCl_2$ will increase.

c. Shift right: The intensity of the violet color of the mixture will decrease.

d. Shift right: The intensity of the violet color of the mixture will decrease.

e. Shift left: The intensity of the brown color of the mixture will increase.

8.56 **a.** The amount of solid LiOH will increase, the amount of solid $LiHCO_3$ will decrease, and the concentration of CO_2 gas will be decreased.

b. The amount of solid $NaHCO_3$ will increase, the amount of solid Na_2O will decrease, and the concentration of CO_2 gas and H_2O gas will decrease.

c. The amount of solid $CaCO_3$ will increase, the amount of solid CaO will decrease, and the concentration of CO_2 gas will decrease.

8.58 **a.** Shift right

b. Shift left

c. Shift right

d. Shift left

e. No shift will occur

f. Shift left

8.60 Apply pressure to the balloon and decrease its volume. This would increase the concentrations of the gaseous reactants A and B inside the balloon and speed up the reaction.

8.62 **a.** Criterion 2

b. Criterion 3

c. Criterion 2

d. Criterion 3

e. Criterion 3

Chapter 9

9.2 **a.** $HBrO_2(aq) \rightarrow H^+(aq) + BrO_2^-(aq)$

b. $HS^-(aq) \rightarrow H^+(aq) + S^{2-}(aq)$

c. $HBr(aq) \rightarrow H^+(aq) + Br^-(aq)$

d. $HC_2H_3O_2(aq) \rightarrow H^+(aq) + C_2H_3O_2^-(aq)$

9.4 **a.** Not an Arrhenius base

b. Arrhenius base: $RbOH(aq) \rightarrow Rb^+(aq) + OH^-(aq)$

c. Not an Arrhenius base

d. Arrhenius base: $Ba(OH)_2(aq) \rightarrow Ba^{2+}(aq) + 2OH^-(aq)$

9.6 **a.** Acids: $HC_2O_4^-$ and H_3O^+

Bases: H_2O and $C_2O_4^{2-}$

b. Acids: HNO_2 and H_3O^+

Bases: H_2O and NO_2^-

c. Acids: H_2O and HPO_4^{2-}

Bases: PO_4^{3-} and OH^-

d. Acids: H_2SO_3 and H_3O^+

Bases: H_2O and HSO_3^-

e. Acids: H_2O and HF

Bases: F^- and OH^-

9.8

	Acid	*Conjugate base*	*Base*	*Conjugate acid*
a.	$HC_2O_4^-$	$C_2O_4^{2-}$	H_2O	H_3O^+
b.	HNO_2	NO_2^-	H_2O	H_3O^+
c.	H_2O	OH^-	PO_4^{3-}	HPO_4^{2-}
d.	H_2SO_3	HSO_3^-	H_2O	H_3O^+
e.	H_2O	OH^-	F^-	HF

9.10 **a.** $HF + H_2O \rightleftarrows H_3O^+ + F^-$

b. $HClO_3 + H_2O \rightleftarrows H_3O^+ + ClO_3^-$

c. $HClO + H_2O \rightleftarrows H_3O^+ + ClO^-$

d. $HS^- + H_2O \rightleftarrows H_3O^+ + S^{2-}$

9.12 **a.** SO_4^{2-}

b. CH_3NH_2

c. ClO_4^-

d. NH_3

e. Cl^-

9.14 **a.** H_2CO_3

b. HS^-

c. H_2S

d. $H_2C_2O_4$

e. $H_2N_2O_2$

9.16 The substance added to complete each equation appears in blue.

a. $H_2AsO_4^-(aq) + NH_3(aq) \rightarrow NH_4^+(aq) + HAsO_4^{2-}(aq)$

b. $C_6H_5NH_2(aq) + H_2O(\ell) \rightarrow C_6H_5NH_3^+(aq) + OH^-(aq)$

c. $S^{2-}(aq) + H_2O(\ell) \rightarrow HS^-(aq) + OH^-(aq)$

d. $(CH_3)_2NH(aq) + HBr(aq) \rightarrow (CH_3)_2NH_2^+(aq) + Br^-(aq)$

e. $CH_3NH_2(aq) + HCl(aq) \rightarrow CH_3NH_3^+(aq) + Cl^-(aq)$

9.18 **a.** $H_3O^+(aq) + NH_2^-(aq) \rightarrow H_2O(\ell) + NH_3(aq)$

b. $H_2PO_4^-(aq) + NH_3(aq) \rightarrow HPO_4^{2-}(aq) + NH_4^+(aq)$

c. $HS_2O_3^-(aq) + OCl^-(aq) \rightarrow S_2O_3^{2-}(aq) + HOCl(aq)$

d. $H_2O(\ell) + ClO_4^-(aq) \rightarrow OH^-(aq) + HClO_4(aq)$

e. $H_2O(\ell) + NH_3(aq) \rightarrow OH^-(aq) + NH_4^+(aq)$

9.20 Hydrocyanic acid

9.22 **a.** Hydrotelluric acid

b. Hypochlorous acid

c. Sulfurous acid

d. Nitrous acid

9.24 Succinicacid

9.26 $HMnO_4$

9.28 **a.** 1.0×10^{-7} M

b. 7.7×10^{-11} M

c. 1.6×10^{-12} M

d. 1.0×10^{-9} M

e. 2.0×10^{-6} M

9.30 **a.** 1.0×10^{-3} M

b. 7.7×10^{-5} M

c. 1.0×10^{-7} M

d. 3.1×10^{-8} M

e. 2.0×10^{-4} M

9.32 In Exercise 9.28: (a) neutral, (b) acidic, (c) acidic, (d) acidic, (e) basic

In Exercise 9.30: (a) acidic, (b) acidic, (c) neutral, (d) basic, (e) acidic

9.34 **a.** Acidic

b. Basic

c. Acidic

d. Basic

9.36 **a.** 8.39, basic

b. 10.97, basic

c. 7.50, basic

d. 1.64, acidic

e. 4.71, acidic

9.38 **a.** 2.66, acidic

b. 11.41, basic

c. 5.12, acidic

d. 10.40, basic

e. 4.94, acidic

9.40 **a.** 6.3×10^{-8} M

b. 1.6×10^{-8} M

c. 3.9

9.42 **a.** $[H_3O^+] = 1.1 \times 10^{-4}M$; $[OH^-] = 8.9 \times 10^{-11}M$

b. $[H_3O^+] = 1.0 \times 10^{-4}M$; $[OH^-] = 1.0 \times 10^{-10}M$

c. $[H_3O^+] = 1.4 \times 10^{-12}M$; $[OH^-] = 7.2 \times 10^{-3}M$

9.44 **a.** 8.9×10^{-9}M, basic

b. 1.2×10^{-4}M, acidic

c. 4.2×10^{-8}M, basic

d. 4.0×10^{-8}M, basic

e. 5.9×10^{-7}M, acidic

9.46 **a.** 1.2×10^{-3}M, acidic

b. 7.8×10^{-5}M, acidic

c. 4.8×10^{-3}M, acidic

d. 8.5×10^{-4}M, acidic

9.48 **a.** Add 1.0 L of dilute (6M) HNO_3 to 1.0 L of pure water and mix well.

b. Add 50 mL of concentrated (15M) NH_3 to 450 mL of pure water and mix well.

c. Add 83 mL of concentrated (12M) HCl to 4.9 L of pure water and mix well.

9.50 **a.** $HCl(aq) + H_2O(\ell) \rightarrow H_3O^+(aq) + Cl^-(aq)$

b. $2HCl(aq) + CaO(s) \rightarrow CaCl_2(aq) + H_2O(\ell)$

c. $2HCl(aq) + Mg(OH)_2(s) \rightarrow MgCl_2(aq) + H_2O(\ell)$

d. $2HCl(aq) + CuCO_3(s) \rightarrow CuCl_2(aq) + CO_2(g) + H_2O(\ell)$

e. $HCl(aq) + KHCO_3(s) \rightarrow KCl(aq) + CO_2(g) + H_2O(\ell)$

f. $2HCl(aq) + Mg(s) \rightarrow MgCl_2(aq) + H_2(g)$

9.52 **a.** Total ionic: $H^+(aq) + Cl^-(aq) + H_2O(\ell) \rightarrow H_3O^+(aq) + Cl^-(aq)$

Net ionic: $H^+_{(aq)} + H_2O_{(\ell)} \rightarrow H_3O^+_{(aq)}$

b. Total ionic: $2H^+_{(aq)} + 2Cl^-_{(aq)} + CaO_{(s)} \rightarrow Ca^{2+}_{(aq)} + 2Cl^-_{(aq)} + H_2O_{(\ell)}$

Net ionic: $2H^+(aq) + CaO(s) \rightarrow Ca^{2+}(aq) + H_2O(\ell)$

c. Total ionic: $2H^+(aq) + 2Cl^-(aq) + Mg(OH)_2(s) \rightarrow Mg^{2+}(aq) + 2Cl^-(aq) + 2H_2O_{(\ell)}$

Net ionic: $2H^+(aq) + Mg(OH)_2(s) \rightarrow Mg^{2+}(aq) + 2H_2O(\ell)$

d. Total ionic: $2H^+(aq) + 2Cl^-(aq) + CaO_3(s) \rightarrow Cu^{2+}(aq) + 2Cl^-(aq) + CO_2(g) + H_2O(\ell)$

Net ionic: $2H^+(aq) + CuCO_3(s) \rightarrow Cu^{2+}(aq) + CO_2(g) + H_2O(\ell)$

e. Total ionic: $H^+(aq) + Cl^-(aq) + KHCO_3(s) \rightarrow K^+(aq) + Cl^-(aq) + CO_2(g) + H_2O(\ell)$

Net ionic: $H^+(aq) + KHCO_3(s) \rightarrow K^+(aq) + CO_2(g) + H_2O(\ell)$

f. Total ionic: $2H^+_{(aq)} + 2Cl^-_{(aq)} + Mg_{(s)} \rightarrow Mg^{2+}_{(aq)} + 2Cl^-_{(aq)} + H_{2(g)}$

Net ionic: $2H^+(aq) + Mg(s) \rightarrow Mg^{2+}(aq) + H_2(g)$

9.54 $Al(OH)_3 + 3HCl \rightarrow AlCl_3 + 3H_2O$

9.56 **a.** Molecular: $Sn(s) + H_2SO_3(aq) \rightarrow SnSO_3(aq) + H_2(g)$

Total ionic: $Sn(s) + 2H^+(aq) + SO_3^{2-}(aq) \rightarrow Sn^{2+}(aq) + SO_3^{2-}(aq) + H_2(g)$

Net ionic: $Sn(s) + 2H^+(aq) \rightarrow Sn^{2+}(aq) + H_2(g)$

b. Molecular: $3Mg(s) + 2H_3PO_4(aq) \rightarrow Mg_3(PO_4)_2(s) + 3H_2(g)$

Total ionic: $3Mg(s) + 6H^+(aq) + 2PO_4^{3-}(aq) \rightarrow Mg_3(PO_4)_2(s) + 3H_2(g)$

Net ionic: $3Mg(s) + 6H^+(aq) + 2PO_4^{3-}(aq) \rightarrow Mg_3(PO_4)_2(s) + 3H_2(g)$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

c. Molecular: $Ca(s) + 2HBr(aq) \rightarrow CaBr_2(aq) + H_2(g)$

Total ionic: $Ca(s) + 2H^+(aq) + 2Br^-(aq) \rightarrow Ca^{2+}(aq) + 2Br^-(aq) + H_2(g)$

Net ionic: $Ca(s) + 2H^+(aq) \rightarrow Ca^{2+}(aq) + H_2(g)$

9.58 **a.** Molecular: $3\,RbOH(aq) + H_3PO_4(aq) \rightarrow Rb_3PO_4(aq) + 3H_2O(\ell)$

Total ionic: $3Rb^+(aq) + 3OH^-(aq) + 3H^+(aq) + PO_4^{3-}(aq) \rightarrow 3Rb^+(aq) + PO_4^{3-}(aq) + 3H_2O(\ell)$

Net ionic: $3OH^-(aq) + 3H^+(aq) \rightarrow 3H_2O(\ell)$

Simplified net ionic: $OH^-(aq) + H^+(aq) \rightarrow H_2O(\ell)$

b. Molecular: $2RbOH(aq) + H_2C_2O_4(aq) \rightarrow Rb_2C_2O_4(aq) + 2H_2O(\ell)$

Total ionic: $2Rb^+(aq) + 2OH^-(aq) + 2H^+(aq) + C_2O_4^{2-}(aq) \rightarrow 2Rb^+(aq) + C_2O_4^{2-}(aq) + 2H_2O(\ell)$

Net ionic: $2OH^-(aq) + 2H^+(aq) \rightarrow 2H_2O(\ell)$

Simplified net ionic: $OH^-(aq) + H^+(aq) \rightarrow H_2O(\ell)$

c. Molecular: $RbOH(aq) + HC_2H_3O_2(aq) \rightarrow RbC_2H_3O_2(aq) + H_2O(\ell)$

Total ionic: $Rb^+(aq) + OH^-(aq) + H^+(aq) + C_2H_3O_2^-(aq) \rightarrow Rb^+(aq) + C_2H_3O_2^-(aq) + H_2O(\ell)$

Net ionic: $OH^-(aq) + H^+(aq) \rightarrow H_2O(\ell)$

9.60 **a.** Polar

b. Polar

c. Nonpolar

9.62 **a.** Cation: NH_4^+; anion: NO_3^-

b. Cation: Ca^{2+}; anion: Cl^-

c. Cation: Mg^{2+}; anion: HCO_3^-

d. Cation: K^+; anion: $C_2H_3O_2^-$

c. Cation: Li^+; anion: HSO_3^-

9.64 **a.** Acid: HNO_3; base: NH_3

b. Acid: HCl; base: $Ca(OH)_2$

c. Acid H_2CO_3; base: $Mg(OH)_2$

d. Acid: $HC_2H_3O_2$; base: KOH

e. Acid: H_2SO_3; base: LiOH

9.66 **a.** 1.3×10^2 g; the product would be $MgSO_4$

b. 1.8×10^2 g; the product would be $Na_2B_4O_7$

9.68 **a.** Acid: HNO_3; solid: $KHCO_3$

b. Acid: HCl; solid: Zn

c. Acid: HBr; solid Li_2O

9.70 **a.** $HNO_3(aq) + KHCO_3(s) \rightarrow KNO_3(aq) + H_2O(\ell) + CO_2(g)$

b. $2HCl(aq) + Zn(s) \rightarrow ZnCl_2(aq) + H_2(g)$

c. $2HBr(aq) + Li_2O(s) \rightarrow 2LiBr(aq) + H_2O(\ell)$

9.72 **a.** 1/2 mol

b. 1/2 mol

c. 1/3 mol

9.74 **a.** 142 mmol/L Na^+

b. 0.7 mmol/L PO_4^{3-}

c. 0.5 mmol/L SO_4^{2-}

9.76 **a.** 3.50×10^{-2} eq; 35.0 meq

b. 4.01×10^{-2} eq; 40.1 meq

c. 1.35×10^{-1} eq; 135 meq

d. 4.17×10^{-2} eq; 41.7 meq

9.78 9.98×10^{-3} mol, 1.74 g

9.80 B, A, C, D

9.82 **a.** Acid order is B, A, C, D.

b. Conjugate base order is D, C, A, B.

9.84 **a.** $HSe^-(aq) \rightleftharpoons H^+(aq) + Se^{2-}(aq)$

$$K_a = \frac{[H^+][Se^{2-}]}{[HSe^-]}$$

b. $H_2BO_3^-(aq) \rightleftharpoons H^+(aq) + HBO_3^{2-}(aq)$

$$K_a = \frac{[H^+][HBO_3^{2-}]}{[H_2BO_3^-]}$$

c. $HBO_3^{2-}(aq) \rightleftharpoons H^+(aq) + BO_3^{3-}(aq)$

$$K_a = \frac{[H^+][BO_3^{3-}]}{[HBO_3^{2-}]}$$

d. $HAsO_4^{2-}(aq) \rightleftharpoons H^+(aq) + AsO_4^{3-}(aq)$

$$K_a = \frac{[H^+][AsO_4^{3-}]}{[HAsO_4^{2-}]}$$

e. $HClO(aq) \rightleftharpoons H^+(aq) + ClO^-(aq)$

$$K_a = \frac{[H^+][ClO^-]}{[HClO]}$$

9.86 According to the definitions given in the chapter, the person should be given the 20% acetic acid solution. If the other solution were the one desired, the term *dilute* should have been used rather than *weak*.

9.88 Titrations are done in order to analyze acids or bases. The amount of acid or base contained in a titrated sample can be determined from the volume of titrant added and the concentration of the titrant.

9.90 **a.** The endpoint and equivalence point will be the same if the chosen indicator changes color at the same pH as the pH of the salt solution produced by the reaction of the acid and base involved in the titration.

b. The endpoint and equivalence point will not be the same if the chosen indicator changes color at a pH that is different from the pH of the salt solution produced by the reaction of the acid and base involved in the titration.

9.92 **a.** 0.100 mol

b. 0.225 mol

9.94 **a.** $NaOH(aq) + HC_2O_2Cl_3(aq) \rightarrow NaC_2O_2Cl_3(aq) + H_2O(\ell)$

b. $2NaOH(aq) + H_2S_2O_6(aq) \rightarrow Na_2S_2O_6(aq) + 2H_2O(\ell)$

c. $4NaOH(aq) + H_4P_2O_6(aq) \rightarrow Na_4P_2O_6(aq) + 4H_2O(\ell)$

9.96 **a.** $2HCl(aq) + Zn(OH)_2(aq) \rightarrow ZnCl_2(aq) + 2H_2O(\ell)$

b. $3HCl(aq) + Tl(OH)_3(aq) \rightarrow TlCl_3(aq) + 3H_2O(\ell)$

c. $HCl(aq) + CsOH(aq) \rightarrow CsCl(aq) + H_2O(\ell)$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

9.98 0.1660 M

9.100 **a.** 33.3 mL
b. 41.7 mL
c. 100. mL
d. 120. mL
e. 85.0 mL
f. 83.3 mL

9.102 **a.** 3.50 M
b. 0.891 M
c. 12.4 M

9.104 122.0 g/mol

9.106 The ions produced when Na_3PO_4 dissolves in water are Na^+ and PO_4^{3-}. The Na^+ ion is the conjugate acid of the strong base NaOH and therefore is a very weak Brønsted acid. The PO_4^{3-} ion is the conjugate base of the weak acid HPO_4^{2-} and therefore will act as a base in a hydrolysis reaction with water and will contribute to the pH of the solution. The reaction is:

$PO_4^{3-}(aq) + H_2O(\ell) \rightarrow HPO_4^{2-}(aq) + OH^-(aq)$

Thus, we see that the hydrolysis reaction contributes OH^- ions to the solution, causing it to have a pH greater than 7.

9.108 **a.** pH greater than 7. The ions produced when the salt dissolves in water are Na^+ and OCl^-. The Na^+ is the conjugate acid of a strong base (NaOH). It will be a weak acid and will not undergo a significant hydrolysis reaction. The OCl^- ion is the conjugate base of a weak acid (HOCl) and will therefore undergo a significant hydrolysis reaction that will contribute to the pH of the solution. The reaction is:

$$OCl^-(aq) + H_2O(\ell) \rightarrow HOCl(aq) + OH^-$$

The OH^- ions produced by this reaction will cause the pH of the solution to be greater than 7.

b. pH greater than 7. The explanation is the same as in part a. The hydrolysis reaction of the CHO_2^- ion is:

$$CHO_2^-(aq) + H_2O(\ell) \rightarrow HCHO_2(aq) + OH^-(aq)$$

c. pH equal to 7. The ions produced when the salt dissolves in water are K^+ and NO_3^-. The K^+ is the conjugate acid of the strong base KOH, and the NO_3^- is the conjugate base of the strong acid HNO_3. Since both ions come from strong sources, they are both weak in their respective behaviors as a conjugate acid or base. As a result, neither of them will undergo a significant hydrolysis reaction that will influence the solution pH.

d. pH greater than 7. The explanation is the same as in part a. The hydrolysis reaction of the PO_4^{3-} ion is:

$$PO_4^{3-}(aq) + H_2O(\ell) \rightarrow HPO_4^{2-}(aq) + OH^-(aq)$$

9.110 Different salts will hydrolyze to different extents in water solution and produce solutions of different pH. In titrations, the pH at the equivalence point is the pH characteristic of a solution of the salt produced by the reaction of the acid and base involved in the titration. Different acids and bases will produce different salts and possibly different solution pH values at the equivalence point. Thus, an indicator must be chosen that will change color at a pH as near as possible to the pH of the salt solution resulting from the titration.

9.112 The buffering anions present in the solution of the two salts are HPO_4^{2-} and $H_2PO_4^-$. When acid is added to the solution, the buffering reaction (like Equation 9.48) is:

$$HPO_4^{2-}(aq) + H^+(aq) \rightleftarrows H_2PO_4^-(aq)$$

When base is added, the buffering reaction (like Equation 9.49) is:

$$H_2PO_4^-(aq) + OH^-(aq) \rightleftarrows HPO_4^{2-}(aq) + H_2O(\ell)$$

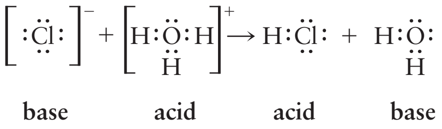
9.114 $HCO_3^-(aq) + H^+(aq) \rightleftarrows H_2CO_3(aq)$

9.116 **a.** pH = 3.85
b. pH = 3.85
c. The difference is that the buffer of part b would have a greater buffer capacity; that is, it could buffer against larger added amounts of acid or base.

9.118 **a.** pH = 4.54
b. pH = 7.81
c. pH = 6.12

9.120 $[HPO_4^{2-}]/[H_2PO_4^-] = 2.8$

9.122 $Cl^-(aq) + H_3O^+(aq) \rightarrow HCl(aq) + H_2O(\ell)$



A base donates a pair of electrons to form a covalent bond, while an acid accepts a pair.

9.124 pH = 6.63

Chapter 10

10.2 **a.** Beta, gamma, and positron
b. Alpha and positron
c. Gamma and neutron

10.4 **a.** A beta particle is identical with an electron.
b. An alpha particle is made up of two protons and two neutrons.
c. A positron is a positively charged electron.

10.6 **a.** The mass number is reduced by 4, and the atomic number is reduced by 2.
b. The mass number is unchanged, and the atomic number is increased by 1.
c. The mass number is unchanged, and the atomic number is reduced by 1.
d. The mass number and atomic number are both unchanged.
e. The mass number is unchanged, and the atomic number is reduced by 1.

10.8 **a.** ${}^{96}_{41}Nb$
b. ${}^{80}_{37}Rb$
b. ${}^{38}_{20}Ca$

10.10 The quantity added to complete each equation appears in blue

a. ${}^{204}_{82}\text{Pb} \rightarrow {}^{200}_{80}\text{Hg} + {}^{4}_{2}\alpha$

b. ${}^{84}_{35}\text{Br} \rightarrow {}^{84}_{36}\text{Kr} + {}^{0}_{-1}\beta$

c. ${}^{41}_{20}\text{Ca} + {}^{0}_{-1}\text{e} \rightarrow {}^{41}_{19}\text{K}$

d. ${}^{149}_{62}\text{Sm} \rightarrow {}^{145}_{60}\text{Nd} + {}^{4}_{2}\alpha$

e. ${}^{34}_{14}\text{Si} + {}^{34}_{15}\text{P} \rightarrow {}^{0}_{-1}\beta$

f. ${}^{15}_{8}\text{O} \rightarrow {}^{0}_{-1}\beta + {}^{15}_{7}\text{N}$

10.12 a. ${}^{157}_{63}\text{Eu} \rightarrow {}^{0}_{-1}\beta + {}^{157}_{64}\text{Gd}$

b. ${}^{190}_{78}\text{Pt} \rightarrow {}^{4}_{2}\alpha + {}^{186}_{76}\text{Os}$

c. ${}^{138}_{62}\text{Sm} + {}^{0}_{-1}e \rightarrow {}^{138}_{61}\text{Pm}$

d. ${}^{188}_{80}\text{Hg} \rightarrow {}^{188}_{79}\text{Au} + {}^{0}_{1}\beta$

e. ${}^{234}_{90}\text{Th} \rightarrow {}^{0}_{-1}\beta + {}^{234}_{91}\text{Pa}$

f. ${}^{218}_{85}\text{At} \rightarrow {}^{4}_{2}\alpha + {}^{214}_{83}\text{Bi}$

10.14 The half-life of a dozen cookies would be the time it takes for the number to be reduced to 6. The half-life of a $500 checking account would be the time it takes to reduce the amount in the account to $250.

10.16 0.56 ng remains

10.18 2.24×10^4 years old

10.20 1.68×10^4 years old

10.22 Long-term exposure to low-level radiation is more likely to cause changes to genetic material in cells. Such changes might result in genetic mutations, cancer, or other serious consequences. Short-term exposure to intense radiation destroys tissue rapidly and causes radiation sickness, which can lead to death, depending on the dose of radiation received.

10.24 A physical unit of radiation, such as a curie, indicates the activity of a source of radiation in terms of the number of nuclear decays that occur per minute. A biological unit of radiation, such as a rem, indicates the damage caused by radiation in living tissue.

10.26 3.2 R of X-rays

10.28 1.7×10^5 disintegrations/s

10.30 Hot spots are concentrations of radioisotope in tissue. Cold spots are areas of tissue that reject or keep out radioactive tracers.

10.32 ${}^{51}_{24}\text{Cr} + {}^{0}_{-1}\text{e} \rightarrow {}^{51}_{23}\text{V}$. The daughter is vanadium-51.

10.34 Use a radioactive isotope of oxygen to make water by burning hydrogen in it. Mix the radioactive water with hydrogen peroxide. Add the catalyst and collect the oxygen gas given off. If the gas is radioactive, it came from the water; if it is not radioactive, it came from the hydrogen peroxide.

10.36 Use a Geiger-Müller tube to measure the radioactivity of a gallon of water that contains the radioisotope. Pour that water into the pool and allow time for it to become completely and uniformly mixed with the water in the pool. Then, remove a gallon of the pool water and measure its radioactivity. For example, if the pool water has a radioactivity one ten-thousandth that of the original tracer-containing water, it means the original gallon of water has been diluted by a factor of 10,000, and therefore the pool contains 10,000 gal of water. Thus, the pool's volume is equal to the factor by which the radioactivity has been reduced.

10.38 ${}^{24}_{12}\text{Mg} + {}^{4}_{2}\alpha \rightarrow {}^{1}_{0}\text{n} + {}^{27}_{14}\text{Si}$

10.40 ${}^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{239}_{94}\text{Pu} + 2\,{}^{0}_{-1}\beta$

10.42 A moderator slows neutrons so that their chances of being captured and interacting with a target nucleus are greater.

10.44 ${}^{66}_{30}\text{Zn} + {}^{1}_{1}p \rightarrow {}^{67}_{31}\text{Ga}$

10.46 $2\,{}^{1}_{1}\text{H} \rightarrow {}^{2}_{1}\text{H} + {}^{0}_{1}\beta$

10.48 Nuclear fission is a process in which heavy nuclei split into smaller nuclei when they are hit by a neutron. Energy is released by the process. An example is:

$${}^{235}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{139}_{54}\text{Xe} + {}^{95}_{38}\text{Sr} + 2\,{}^{1}_{0}\text{n}$$

When nuclear fusion occurs, small nuclei fuse together and form heavier nuclei. Energy is released by the process. An example is: ${}^{1}_{1}\text{H} + {}^{2}_{1}\text{H} \rightarrow {}^{3}_{2}\text{He} + \gamma$

10.50 ${}^{238}_{94}\text{Pu} \rightarrow {}^{4}_{2}\alpha + {}^{234}_{92}\text{U}$

10.52 The positive nuclei of the reacting hydrogen atoms naturally repel each other. In order to overcome this repulsion and get close enough together to fuse, the nuclei must have very high speeds (kinetic energy). The necessary high kinetic energy can only be obtained by the nuclei at very high temperatures. Remember, temperature is a measurement of the average kinetic energy of particles in matter.

10.54 3.5×10^{20} counts/minute $= 1.6 \times 10^8$ Ci

Chapter 11

11.2 Hair, skin, clothing, paper, plastic, carpet

11.4 They all contain carbon.

11.6 a. Inorganic

b. Organic

c. Inorganic

d. Inorganic

11.8 The majority of all compounds that are insoluble in water are organic. Organic compounds are often nonpolar, and nonpolar compounds are insoluble in polar water.

11.10 a. A relatively low melting point is characteristic of organic compounds.

b. Solubility in water and lack of flammability is typical of inorganic compounds.

c. Conductivity of water solutions is typical for ionic substances (inorganic compounds).

d. Inorganics often have high melting points.

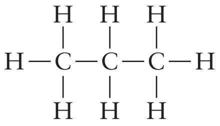
11.12 Organic compounds do not readily accept electrons to transport them, thus making the flow of electrical current impossible.

11.14 The ability of carbon to bond to itself repeatedly; isomerism.

11.16 The *s* orbital of the hydrogen overlaps with the sp^3 orbital of carbon.

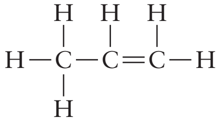
11.18 A *p* orbital and an sp^3 orbital both have a two-lobed shape. A *p* orbital has equal-sized lobes, whereas an sp^3 orbital has different-sized lobes.

11.20 a.



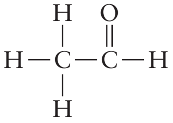
$H-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-H$

b.



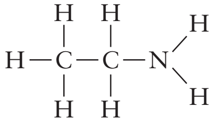
$H-\underset{H}{\overset{H}{C}}-\overset{H}{C}=\overset{H}{C}-H$

c.



$H-\underset{H}{\overset{H}{C}}-\overset{O}{\overset{\|}{C}}-H$

d.



11.22 b, d

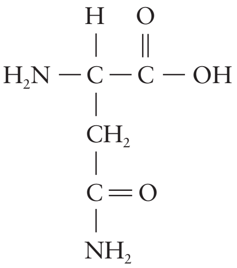
11.24 The isomers are (a), (b), (e), and (f); all have the molecular formula $C_3H_6O_2$.

- **a.** $C_3H_6O_2$
- **b.** $C_3H_6O_2$
- **c.** C_3H_8O
- **e.** $C_3H_6O_2$
- **f.** $C_3H_6O_2$
- **g.** $C_3H_8O_2$

11.26 a. Correct

- **b.** Incorrect, the center carbon has five bonds.
- **c.** Incorrect, the carbon to the right has five bonds.
- **d.** Incorrect, the second carbon from the left has only three bonds.

11.28

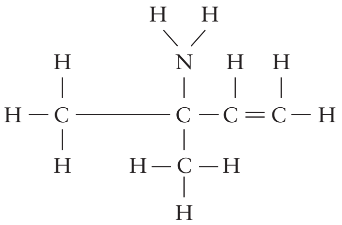


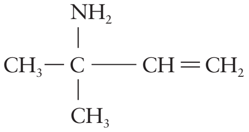
11.30 a. Expanded structural formula

- **b.** Condensed structural formula
- **c.** Molecular formula
- **d.** Condensed structural formula

11.32 Expanded Condensed

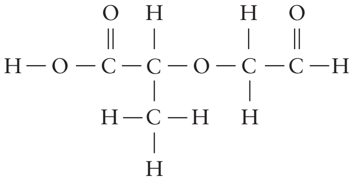
a.

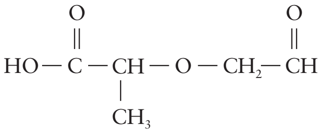




$CH_3-\underset{CH_3}{\overset{NH_2}{C}}-CH=CH_2$

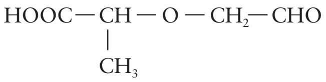
b.





$HO-\overset{O}{\overset{\|}{C}}-\underset{CH_3}{CH}-O-CH_2-\overset{O}{\overset{\|}{CH}}$

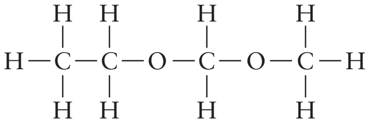
or



$HOOC-\underset{CH_3}{CH}-O-CH_2-CHO$

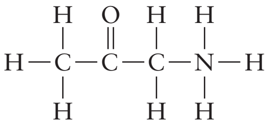
11.34

a.



$H-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{C}}-O-\underset{H}{\overset{H}{C}}-O-\underset{H}{\overset{H}{C}}-H$

b.



$H-\underset{H}{\overset{H}{C}}-\overset{O}{\overset{\|}{C}}-\underset{H}{\overset{H}{C}}-\underset{H}{\overset{H}{N}}-H$

11.36 $C_{12}H_{26}$, $CH_3(CH_2)_{10}CH_3$

11.38 a. Saturated

- **b.** Unsaturated
- **c.** Unsaturated
- **d.** Saturated

11.40 a. C_nH_{2n+2}, heptane has 16 hydrogens.

- **b.** If $H_{2n+2} = 22$, $n = 10 = C_{10.}$

11.42 a. Branched

- **b.** Normal
- **c.** Normal
- **d.** Normal

11.44 Different conformations of an alkane are not considered structural isomers because the bonding order is not changed in the different conformations, which means that the conformations correspond to the same molecule. Two structures would be structural isomers only if bonds were broken and remade to convert one into the other.

11.46 a. The same compound, 2-methylbutane.

- **b.** The same compound, 2-methylbutane.
- **c.** Structural isomers.
- **d.** The same compound, butane.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

11.48 **a.** Six

b. Five

c. Seven

11.50 **a.** Propyl

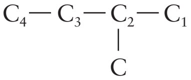
b. Ethyl

c. *sec*-butyl

d. *t*-butyl

11.52 Note: The hydrogen atoms have been removed from the following structures in order to facilitate the identification of the parent chain.

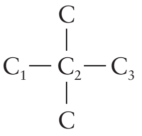
a.



$C_4-C_3-\underset{C}{C_2}-C_1$

2-methylbutane

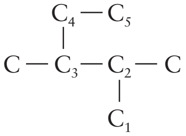
b.



$C_1-\underset{C}{\overset{C}{C_2}}-C_3$

2,2-dimethylpropane

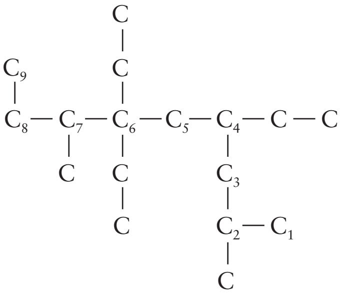
c.



$C-\overset{C_4-C_5}{C_3}-\underset{C_1}{C_2}-C$

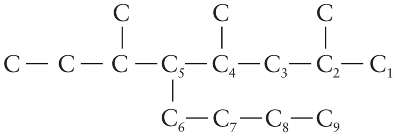
2,3-dimethylpentane

d.



4,6,6-triethyl-2,7-dimethylnonane

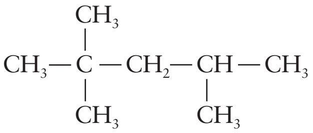
e.



5-*sec*-butyl-2,4-dimethylnonane

11.54

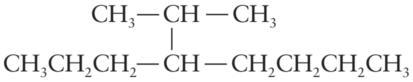
a.



$CH_3-\underset{CH_3}{\overset{CH_3}{C}}-CH_2-\underset{CH_3}{CH}-CH_3$

2,2,4-trimethylpentane

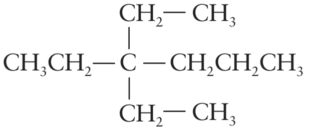
b.



$CH_3CH_2CH_2-\overset{CH_3-CH-CH_3}{CH}-CH_2CH_2CH_2CH_3$

4-isopropyloctane

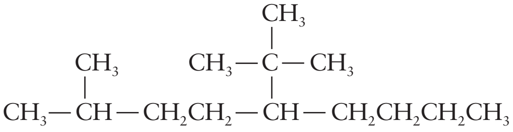
c.



$CH_3CH_2-\underset{CH_2-CH_3}{\overset{CH_2-CH_3}{C}}-CH_2CH_2CH_3$

3,3-diethylhexane

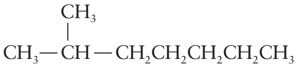
d.



$CH_3-\overset{CH_3}{CH}-CH_2CH_2-\overset{CH_3-\overset{CH_3}{C}-CH_3}{CH}-CH_2CH_2CH_2CH_3$

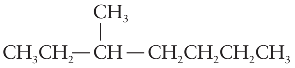
5-*t*-butyl-2-methylnonane

11.56



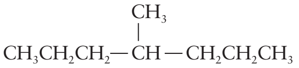
$CH_3-\overset{CH_3}{CH}-CH_2CH_2CH_2CH_2CH_3$

2-methylheptane



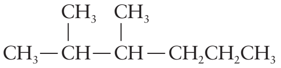
$CH_3CH_2-\overset{CH_3}{CH}-CH_2CH_2CH_2CH_3$

3-methylheptane



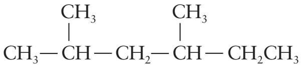
$CH_3CH_2CH_2-\overset{CH_3}{CH}-CH_2CH_2CH_3$

4-methylheptane



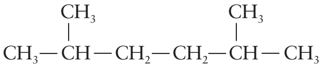
$CH_3-\overset{CH_3}{CH}-\overset{CH_3}{CH}-CH_2CH_2CH_3$

2,3-dimethylhexane



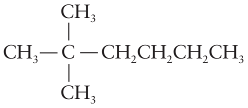
$CH_3-\overset{CH_3}{CH}-CH_2-\overset{CH_3}{CH}-CH_2CH_3$

2,4-dimethylhexane



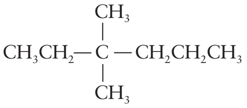
$CH_3-\overset{CH_3}{CH}-CH_2-CH_2-\overset{CH_3}{CH}-CH_3$

2,5-dimethylhexane



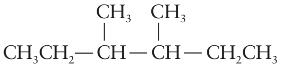
$CH_3-\underset{CH_3}{\overset{CH_3}{C}}-CH_2CH_2CH_2CH_3$

2,2-dimethylhexane



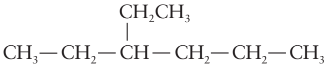
$CH_3CH_2-\underset{CH_3}{\overset{CH_3}{C}}-CH_2CH_2CH_3$

3,3-dimethylhexane



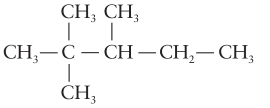
$CH_3CH_2-\overset{CH_3}{CH}-\overset{CH_3}{CH}-CH_2CH_3$

3,4-dimethylhexane



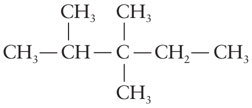
$CH_3-CH_2-\overset{CH_2CH_3}{CH}-CH_2-CH_2-CH_3$

3-ethylhexane



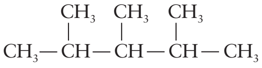
$CH_3-\underset{CH_3}{\overset{CH_3}{C}}-\overset{CH_3}{CH}-CH_2-CH_3$

2,2,3-trimethylpentane



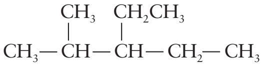
$CH_3-\overset{CH_3}{CH}-\underset{CH_3}{\overset{CH_3}{C}}-CH_2-CH_3$

2,3,3-trimethylpentane



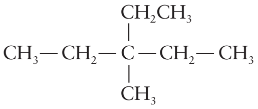
$CH_3-\overset{CH_3}{CH}-\overset{CH_3}{CH}-\overset{CH_3}{CH}-CH_3$

2,3,4-trimethylpentane



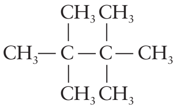
$CH_3-\overset{CH_3}{CH}-\overset{CH_2CH_3}{CH}-CH_2-CH_3$

3-ethyl-2-methylpentane



$CH_3-CH_2-\underset{CH_3}{\overset{CH_2CH_3}{C}}-CH_2-CH_3$

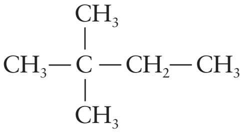
3-ethyl-3-methylpentane



$CH_3-\underset{CH_3}{\overset{CH_3}{C}}-\underset{CH_3}{\overset{CH_3}{C}}-CH_3$

2,2,3,3-tetramethylbutane

11.58 **a.** Incorrect = 2,2-methylbutane

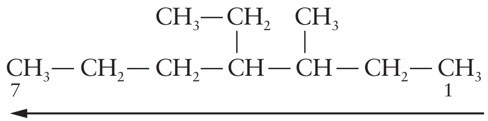


$CH_3-\underset{CH_3}{\overset{CH_3}{C}}-CH_2-CH_3$

corrected = 2,2-dimethylbutane

When more than one of the same alkyl group is present, the prefix *di*- should be added to the alkyl group name.

b. Incorrect = 4-ethyl-5-methylheptane

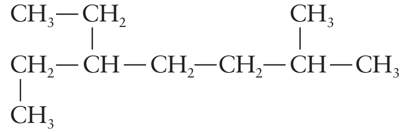


$$\underset{7}{CH_3}-CH_2-CH_2-\overset{CH_3-CH_2}{\overset{|}{CH}}-\overset{CH_3}{\overset{|}{CH}}-CH_2-\underset{1}{CH_3}$$

corrected = 4-ethyl-3-methylheptane

The parent chain was not numbered so that the attached groups were on the lowest numbered carbon atoms.

c. Incorrect = 2-ethyl-1,5-dimethylhexane



$$\underset{\underset{CH_3}{|}}{CH_2}-\overset{CH_3-CH_2}{\overset{|}{CH}}-CH_2-CH_2-\overset{CH_3}{\overset{|}{CH}}-CH_3$$

corrected = 5-ethyl-2-methylheptane

The longest chain (7 C) was not identified as the parent chain.

11.60 The general formula for cycloalkanes is C_nH_{2n}.

11.62 **a.** C_nH_{2n}. If $n = 9$, $2n = 18$; C_9H_{18}

b. C_nH_{2n}. If $2n = 24$, $n = 12$; $C_{12}H_{24}$

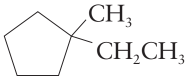
11.64 **a.** Two

b. One

c. Zero

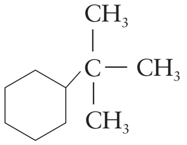
11.66

a.



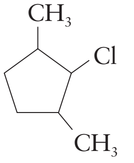
1-ethyl-1-methylcyclopentane

b.



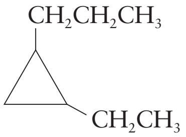
t-butylcyclohexane

c.



2-chloro-1,3-dimethylcyclopentane

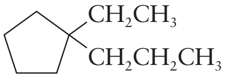
d.



1-ethyl-2-propylcyclopropane

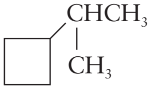
11.68

a.



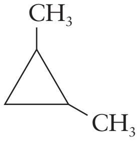
1-ethyl-1-propylcyclopentane

b.



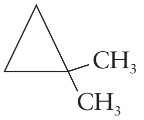
isopropylcyclobutane

c.



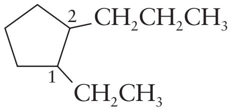
1,2-dimethylcyclopropane

11.70 **a.**



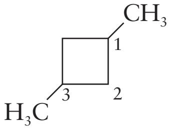
The locations of the methy groups are not identified. This possible structure is 1,1-dimethylcyclopropane.

b.



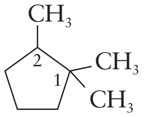
Unless it results in a higher number, the group coming first alphabetically is given the lower number: 1-ethyl-2-propylcyclopentane.

c.



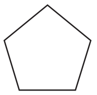
Lower numbers can be assigned: 1,3-dimethylcyclobutane.

d.

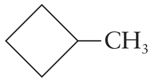


Lower numbers can be assigned: 1,1,2-trimethylcyclopentane.

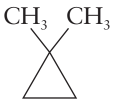
11.72



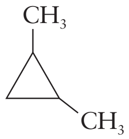
cyclopentane



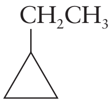
methylcyclobutane



1,1-dimethylcyclopropane



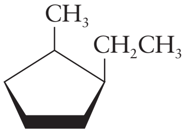
1,2-dimethylcyclopropane



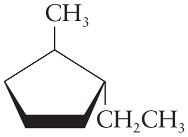
ethylcyclopropane

11.74 Structural isomers differ in the order the atoms are bonded together. *Cis-trans* isomers have the same atomic bonding order, but differ in the way the branches are oriented in space. For *cis-trans* isomers to be possible, the structure must have some feature that prevents free rotation about the bond in question. This occurs in cycloalkanes.

11.76 **a.**



cis-1-ethyl-2-methylcyclopentane

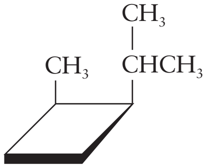


trans-1-ethyl-2-methylcyclopentane

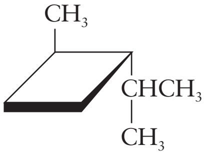
b. Cannot

c. Cannot

d.



cis-1-methyl-2-propylcyclobutane



trans-1-methyl-2-propylcyclobutane

11.78 **a.** *trans*-1-ethyl-2-methylcyclopropane
b. *cis*-1-bromo-2-chlorocyclopentane
c. *trans*-1-methyl-2-propylcyclobutane
d. *trans*-1,3-dimethylcyclohexane

11.80 **a.** Liquid
b. No
c. Yes
d. Less dense

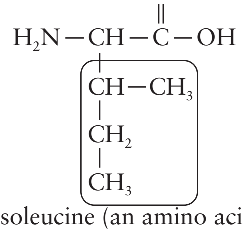
11.82 2-methylheptane

11.84 **a.** Hexane
b. Decane

11.86 **a.** Gas
b. Solid
c. Liquid

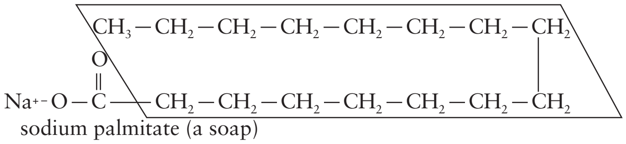
11.88

a.



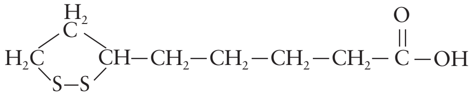
isoleucine (an amino acid)

b.



sodium palmitate (a soap)

c.



lipoic acid (a component of a coenzyme)

11.90 **a.** $2C_4H_{10} + 13O_2 \rightarrow 8CO_2 + 10H_2O$
b. $C_5H_{12} + 8O_2 \rightarrow 5CO_2 + 6H_2O$
c. $C_4H_8 + 6O_2 \rightarrow 4CO_2 + 4H_2O$

11.92 $2C_6H_{14} + 13O_2 \rightarrow 12CO + 14H_2O$

11.94 Because of the rigid structure of cycloalkanes, stronger dispersion forces can develop between molecules. This increase of intermolecular attraction causes an increase in boiling point.

11.96 Pentane: 414.5 torr; hexane: 113.9 torr; heptane: 37.2 torr

11.98 13 L of air

11.100 The study of organic compounds might be important to someone interested in the health or life sciences because living organisms are composed of mostly organic compounds and most medications are also organic compounds.

11.102 The low melting point of the ski wax indicates that the molecules in the ski wax have weak forces between the molecules. (*Note:* The forces are dispersion forces.)

11.104 If carbon did not form hybridized orbitals, the formula of the simplest compound of carbon and hydrogen would be C_2H_4 because each carbon atom would have two unpaired electrons that would each pair with the unpaired electron in a hydrogen atom and the carbon atoms could share their two lone pairs of electrons in a double bond. With this arrangement, both carbon atoms would have a complete octet and each hydrogen atom would have a complete valence shell with two electrons.

11.106 If a semi truck loaded with cyclohexane overturns during a rainstorm, spilling its contents over the road embankment and the rain continues, then the cyclohexane will float on top of the standing water and run off along the water drainage route. Some of the cyclohexane will probably also evaporate because it has weak intermolecular forces.

11.108 Alkanes do not mix with water and are less dense than water; therefore, when an oil spill occurs, the oil floats on top of the water. Alkanes are relatively unreactive; therefore, short of burning the oil, a chemical reaction cannot be performed to "neutralize" the oil spill. Burning the oil is not a good idea because of the wildlife that quickly becomes disabled by contact with the oil and because crude oil often contains compounds (other than the pure hydrocarbons) that may produce toxic products when burned. Birds that come into contact with the oil must be cleaned with soap before they are able to fly again. A bird will try to clean the oil off of its own feathers and ingest the oil, which does damage to its internal organs. Sea otters and killer whales as well as small organisms at the bottom of the food chain are also impacted by contact with oil.

Chapter 12

12.2 An alkene contains one or more C$=$C bonds.

An alkyne contains one or more C$\equiv$C bonds.

An aromatic hydrocarbon contains the characteristic benzene ring or similar feature.

12.4
- **a.** unsaturated, alkene
- **b.** unsaturated, alkene
- **c.** unsaturated, alkene
- **d.** not unsaturated
- **e.** unsaturated, alkyne

12.6
- **a.** Cannot exist, because carbon atoms 1 and 2 each have five bonds.
- **c.** Cannot exist, because carbon 2 has five bonds.

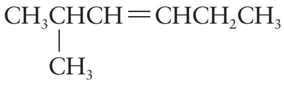
12.8 A: Br

B: H

C:$-CH_3$

D: $-CH_3$

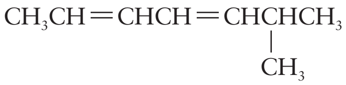
12.10 **a.**



$CH_3\underset{\underset{\displaystyle CH_3}{|}}{C}HCH=CHCH_2CH_3$

2-methyl-3-hexene

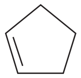
b.



$CH_3CH=CHCH=CH\underset{\underset{\displaystyle CH_3}{|}}{C}HCH_3$

6-methyl-2,4-heptadiene

c.

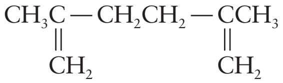


cyclopentene

d. $CH_3-C\equiv C-CH_2CH_3$

2-pentyne

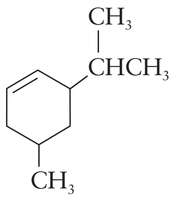
e.



$CH_3\underset{\underset{\displaystyle CH_2}{\|}}{C}-CH_2CH_2-\underset{\underset{\displaystyle CH_2}{\|}}{C}CH_3$

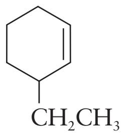
2,5-dimethyl-1,5-hexadiene

f.



3-isopropyl-5-methylcyclohexene

g.

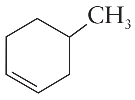


3-ethylcyclohexene

12.12
- **a.** cyclopentylethene
- **b.** cyclobutene
- **c.** 1-butene
- **d.** 2-methylpropane
- **e.** propyne

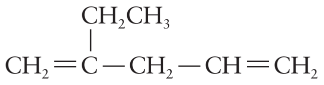
12.14

a.



4-methylcyclohexene

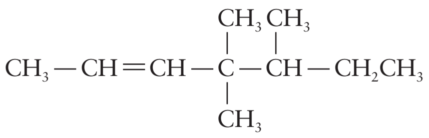
b.



$CH_2=\overset{\overset{\displaystyle CH_2CH_3}{|}}{C}-CH_2-CH=CH_2$

2-ethyl-1,4-pentadiene

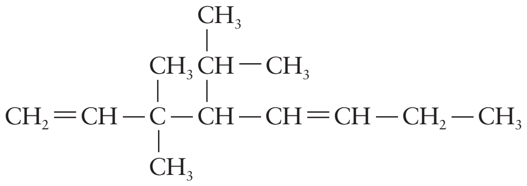
c.



$CH_3-CH=CH-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-\overset{\overset{\displaystyle CH_3}{|}}{C}H-CH_2CH_3$

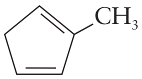
4,4,5-trimethyl-2-heptyne

d.



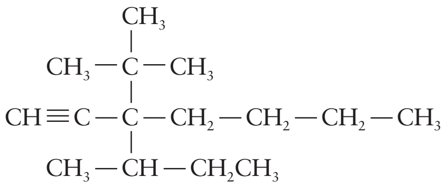
4-isopropyl-3,3-dimethyl-1,5-octadiene

e.



2-methyl-1,3-cyclopentadiene

f.



3-*sec*-butyl-3-*t*-butyl-1-heptyne

12.16

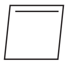
a. $CH_3CH_2-C\equiv C-H$ or $CH_3-C\equiv C-CH_3$

1-butyne 2-butyne

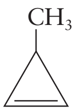
b. $H_2C=CH-CH=CH_2$ or $H_2C=C=CH-CH_3$

1,3-butadiene 1,2-butadiene

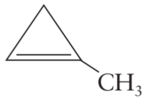
c.



or



or

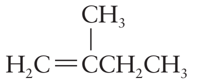


cyclobutene 3-methylcyclopropene 1-methylcyclopropene

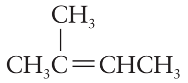
Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

12.18 $H_2C{=}CHCH_2CH_2CH_3$
1-pentene

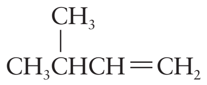
$CH_3CH{=}CHCH_2CH_3$
2-pentene


$H_2C{=}\overset{\overset{\displaystyle CH_3}{|}}{C}CH_2CH_3$

2-methyl-1-butene

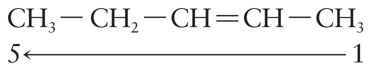

$CH_3\overset{\overset{\displaystyle CH_3}{|}}{C}{=}CHCH_3$

2-methyl-2-butene

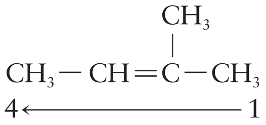

$CH_3\overset{\overset{\displaystyle CH_3}{|}}{C}HCH{=}CH_2$

3-methyl-1-butene

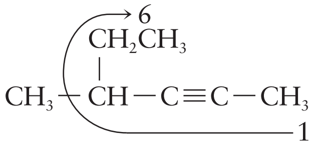
12.20 **a.** Incorrect = 3-pentene
corrected = 2-pentene


$$\underset{5 \longleftarrow\!\!\longleftarrow\!\!\longleftarrow 1}{CH_3-CH_2-CH{=}CH-CH_3}$$

b. Incorrect = 3-methyl-2-butene
corrected = 2-methyl-2-butene


$$\underset{4 \longleftarrow\!\!\longleftarrow\!\!\longleftarrow 1}{CH_3-CH{=}\overset{\overset{\displaystyle CH_3}{|}}{C}-CH_3}$$

c. Incorrect = 2-ethyl-3-pentyne
corrected = 4-methyl-2-hexyne


$$\underset{6 \longleftarrow\!\!\longleftarrow\!\!\longleftarrow 1}{CH_3-\overset{\overset{\displaystyle CH_2CH_3}{|}}{CH}-C{\equiv}C-CH_3}$$

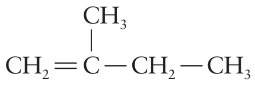
12.22 **a.** 4-methyl-3-heptene **c.** 1,3-cyclopentadiene
b. 2,5-dimethyl-1-hexene **d.** 4,4-dimethyl-1-cyclohexene

12.24 Carbon atoms in a double bond each have 3 sp^2 hybrid orbitals as well 1 unhybridized p orbital.

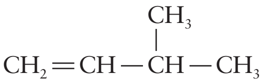
12.26 Carbon atoms in a double bond have a trigonal planar geometry where the two atoms attached to the double bonded carbon atom as well as the other carbon atom in the double bond are in the same plane, separated by bond angles of 120°.

12.28 **a.** Alkenes that do not show *cis-trans* isomerism. There are four compounds.

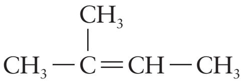
$CH_2{=}CH-CH_2-CH_2-CH_3$
1-pentene


$CH_2{=}\overset{\overset{\displaystyle CH_3}{|}}{C}-CH_2-CH_3$

2-methyl-1-butene


$CH_2{=}CH-\overset{\overset{\displaystyle CH_3}{|}}{CH}-CH_3$

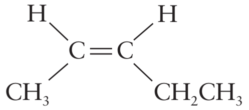
3-methyl-1-butene

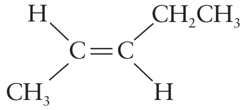

$CH_3-\overset{\overset{\displaystyle CH_3}{|}}{C}{=}CH-CH_3$

2-methyl-2-butene

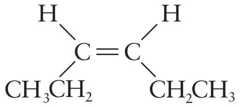
b. Alkenes that do show *cis-trans* isomerism. There is one *cis-* and one *trans-* compound.

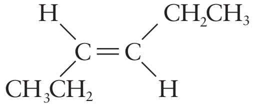
$CH_3-CH{=}CH-CH_2-CH_3$
2-pentene can exist as *cis-* or *trans-*

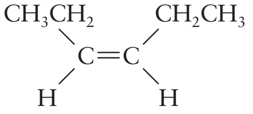

cis-2-pentene

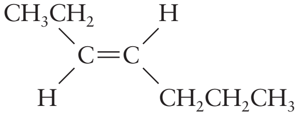

trans-2-pentene

12.30 **a.** and **c.** cannot have cis- and trans-isomers.

b. 
cis-3-hexene


trans-3-hexene

12.32 **a.** 

b. 

12.34 **a.** 1,1,2,2-tetrachloroethene
b. *cis*-2-pentene
c. *trans*-3-hexene
d. propene

12.36 Both alkanes and alkenes are nonpolar compounds that are insoluble in water, less dense than water, and soluble in nonpolar solvents.

12.38 **a.** false
b. true
c. false
d. false

12.40

a.	$A_2 + C_3H_6 \rightarrow C_3H_6A_2$	addition
b.	$A_2 + C_3H_6 \rightarrow C_3H_5A + HA$	not addition (substitution)
c.	$HA + C_4H_8 \rightarrow C_4H_9A$	addition
d.	$3\ O_2 + C_2H_4 \rightarrow 2\ CO_2 + H_2O$	not addition (combustion)
e.	$C_7H_{16} \rightarrow C_7H_8 + 4\ H_2$	not addition (decomposition)

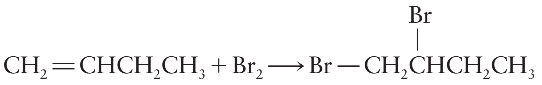
12.42 **a.** $CH_2{=}CH_2 + Br_2 \longrightarrow Br-CH_2CH_2-Br$

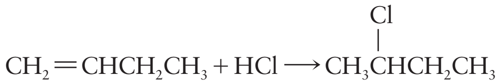
b. $CH_2{=}CH_2 + HCl \longrightarrow CH_3CH_2-Cl$

c. $CH_2{=}CH_2 + H_2 \xrightarrow{Pt} CH_3CH_3$

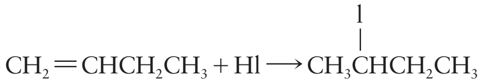
d. $CH_2{=}CH_2 + Hl \longrightarrow CH_3CH_2-l$

12.44

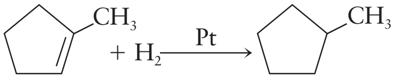
a. 
$CH_2{=}CHCH_2CH_3 + Br_2 \longrightarrow Br-CH_2\overset{\overset{\displaystyle Br}{|}}{C}HCH_2CH_3$

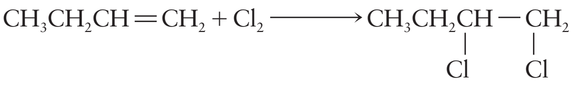
b. 
$CH_2{=}CHCH_2CH_3 + HCl \longrightarrow CH_3CH(Cl)CH_2CH_3$

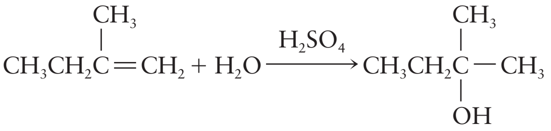
c. $CH_2{=}CHCH_2CH_3 + H_2 \xrightarrow{Pt} CH_3CH_2CH_2CH_3$

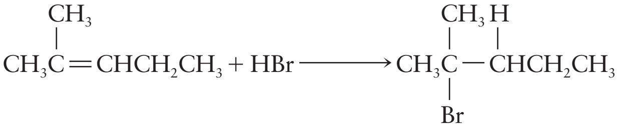
d. 
$CH_2{=}CHCH_2CH_3 + HI \longrightarrow CH_3CH(I)CH_2CH_3$

12.46

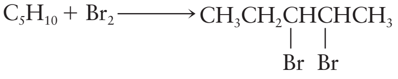
a. 

b. 
$CH_3CH_2CH{=}CH_2 + Cl_2 \longrightarrow CH_3CH_2CH(Cl){-}CH_2(Cl)$

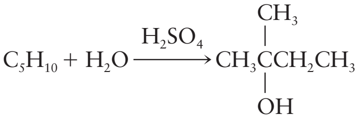
c. 
$CH_3CH_2C(CH_3){=}CH_2 + H_2O \xrightarrow{H_2SO_4} CH_3CH_2C(CH_3)(OH){-}CH_3$

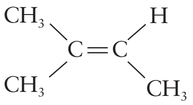
d. 
$CH_3C(CH_3){=}CHCH_2CH_3 + HBr \longrightarrow CH_3C(CH_3)(Br){-}CH(H)CH_2CH_3$

12.48

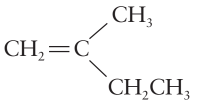
a. 
$C_5H_{10} + Br_2 \longrightarrow CH_3CH_2CH(Br)CH(Br)CH_3$ $CH_3CH_2CH{=}CHCH_3$

b. $C_5H_{10} + H_2 \xrightarrow{Pt} CH_3CH_2CH_2CH_2CH_3$ $CH_3CH_2CH_2CH{=}CH_2$ or $CH_3CH_2CH{=}CHCH_3$

c. 
$C_5H_{10} + H_2O \xrightarrow{H_2SO_4} CH_3C(CH_3)(OH)CH_2CH_3$



or



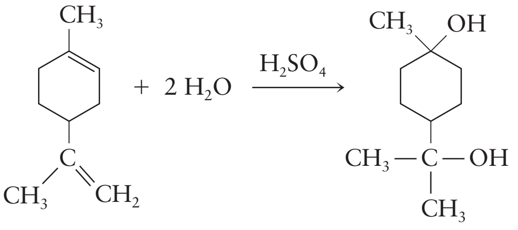
12.50 a. F_2

b. H_2 with Pt catalyst

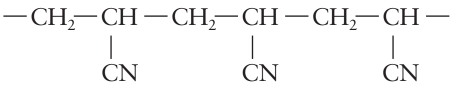
c. HBr

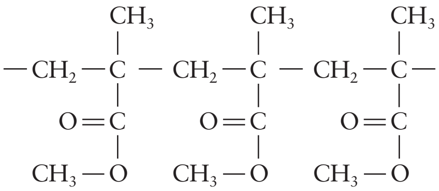
d. H_2O with H_2SO_4 catalyst

12.52 An important commercial application of hydrogenation is the hydrogenation of liquid vegetable oils to produce a solid vegetable shortening.

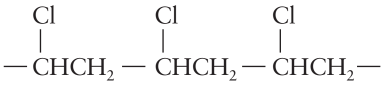
12.54 

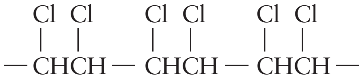
12.56 a. Teflon $-CF_2-CF_2-CF_2-CF_2-CF_2-CF_2-$

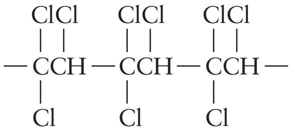
b. Orlon 
$-CH_2-CH(CN)-CH_2-CH(CN)-CH_2-CH(CN)-$

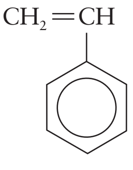
c. Lucite 

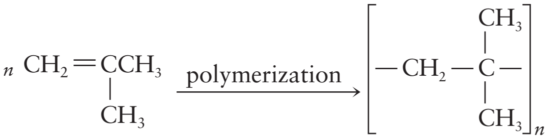
12.58 a. $-CH_2CH_2-CH_2CH_2-CH_2CH_2-$

b. 
$-CH(Cl)CH_2-CH(Cl)CH_2-CH(Cl)CH_2-$

c. 
$-CH(Cl)CH(Cl)-CH(Cl)CH(Cl)-CH(Cl)CH(Cl)-$

d. 
$-CCl_2CH(Cl)-CCl_2CH(Cl)-CCl_2CH(Cl)-$

12.60 

12.62 
$n\ CH_2{=}C(CH_3)CH_3 \xrightarrow{\text{polymerization}} \left[-CH_2-C(CH_3)_2-\right]_n$

12.64

a.	Styrofoam	Food coolers, drinking cups, insulation
b.	Acrilan	Carpets, fabrics
c.	Plexiglass	Airplane windows, paint, contact lenses, fiber optics
d.	PVC	Synthetic leather, floor tiles, garden hoses, water pipe
e.	Polypropylene	Carpet fiber, pipes, bottles, artificial turf

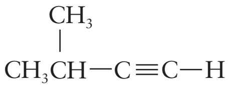
12.66 A triple bond of an alkyne is composed of 1 sigma and two pi bonds.

12.68 *Cis-trans* isomerism is not possible in alkynes because the geometry around a triple bond is linear. Each carbon atom in the triple bond only has one other attached group, unlike each carbon atom in a double bond that has two attached groups.

12.70 Alkynes are insoluble in water, are less dense than water, have relatively low melting and boiling points, and are flammable. They undergo addition reactions, like alkenes, but consume twice as much addition reagent for the reaction to go to completion.

12.72 $H{-}C{\equiv}C{-}CH_2CH_2CH_3$
1-pentyne

$CH_3{-}C{\equiv}C{-}CH_2CH_3$
2-pentyne


$CH_3\overset{CH_3}{\overset{|}{C}}H{-}C{\equiv}C{-}H$
3-methyl-1-butyne

12.74 Unhydridized *p* orbitals

12.76 Aromatic refers to compounds containing the benzene ring. Aliphatic substances do not contain a benzene ring.

12.78 In cyclopentane, attached groups are located above and below the plane of the ring. In benzene, attached groups are located in the same plane as the ring.

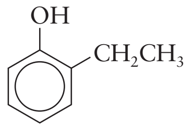
12.80 **a.** 1,3,5-trimethylbenzene
b. 1,4-diethylbenzene

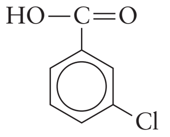
12.82 **a.** 3-phenyl-1-pentene
b. 2,5-diphenylhexane

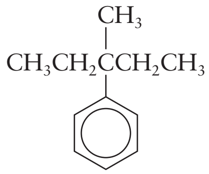
12.84 **a.** *m*-bromophenol
b. *p*-ethylaniline

12.86 **a.** 2,6-dibromobenzoic acid
b. 3-chloro-5-ethyltoluene

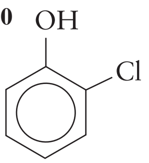
12.88

a.


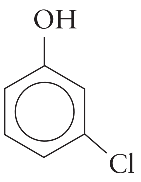
b.


c.


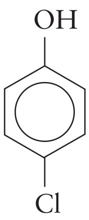
12.90

a.


2-chlorophenol
or
o-chlorophenol

b.


3-chlorophenol
or
m-chlorophenol

c.


4-chlorophenol
or
p-chlorophenol

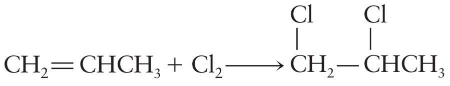
12.92 Benzene does not readily undergo addition reactions characteristic of other unsaturated compounds because the delocalized pi cloud of the benzene ring makes the ring so stable that addition reactions do not occur. An addition reaction would result in the loss of one of the double bonds, and consequently, disrupt the delocalized Pi system. This is not favored because it results in a loss of stability. Benzene, therefore, undergoes substitution reactions instead of addition reactions.

12.94

a.	A solvent	benzene, toluene
b.	A vitamin	riboflavin
c.	An essential amino acid	phenylalanine
d.	Starting material for dyes	aniline

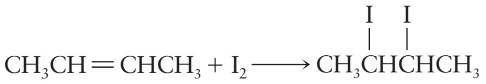
12.96 Alkynes have slightly higher boiling points and densities than structurally equivalent alkanes because the linear alkyne molecules can pack more closely together than the alkane molecules. This close packing allows for stronger dispersion forces, which cause the alkynes to have higher boiling points and densities than structurally equivalent alkanes.

12.98


$CH_2{=}CHCH_3 + Cl_2 \longrightarrow \overset{Cl}{\overset{|}{C}}H_2{-}\overset{Cl}{\overset{|}{C}}HCH_3$

1,2-dichloropropane

12.100 When 25.0 g of 2-butene reacts with 25.0 g of iodine, iodine is the limiting reactant. Only 0.0985 moles of product will be produced.


$CH_3CH{=}CHCH_3 + I_2 \longrightarrow CH_3\overset{I}{\overset{|}{C}}H\overset{I}{\overset{|}{C}}HCH_3$

$$25.0\text{ g }C_4H_8\left(\frac{1\text{ mol }C_4H_8I_2}{56.1\text{ g }C_4H_8}\right) = 0.446\text{ g mol }C_4H_8I_2$$

$$25.0\text{ g }I_2\left(\frac{1\text{ mol }C_4H_8I_2}{254\text{ g }I_2}\right) = 0.0984\text{ g mol }C_4H_8I_2$$

12.102 Propene does not exhibit *cis-trans* isomerism because one of the carbon atoms in the double bond is also bonded to two hydrogen atoms. In order to exhibit *cis-trans* isomerism, both carbon atoms in the double bond must also be bonded to two unique groups.

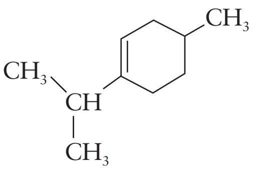
12.104

$$5.0\ \times 10^4\text{ u}\left(\frac{1\text{ ethylene monomer}}{28.0\text{ u}}\right) = 1.8 \times 10^3\text{ ethylene monomers}$$

12.106 Addition polymers form a large extended structure. Polyvinyl acetate prevents the formation of sharp fragments in automobile safety glass because it holds the glass together on a flexible surface after the glass is broken. The copolymer of styrene and 1,3-butadiene allows a large flexible bubble to be formed by the girl chewing gum.

12.108 The polymer that produces hydrogen cyanide, HCN, is polyacrylonitrile. The polymer that produces hydrogen chloride, HCl, is poly (vinyl chloride).

12.110



1-isopropyl-4-methylcyclohexene
(menthene)

Chapter 13

13.2 R—O—R

13.4 **a.** 2-propanol

b. 3-methyl-3-pentanol

c. 5-bromo-3-ethyl-1-pentanol

d. 2-isopropyl-1-methylcyclopropanol

e. 2,2-dimethylcyclopentanol

f. 1,2-cyclopentanediol

g. 1,2,4-hexanetriol

13.6 **a.** Methanol

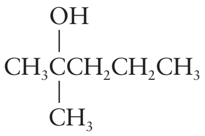
b. 2-propanol

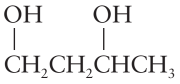
c. Ethanol

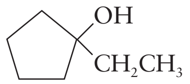
d. 1,2-ethanediol

e. 1,2,3-propanetriol

13.8

a. 
$\mathrm{CH_3\overset{OH}{\underset{CH_3}{C}}CH_2CH_2CH_3}$

b. 
$\mathrm{\overset{OH}{C}H_2CH_2\overset{OH}{C}HCH_3}$

c. 

13.10 **a.** 1,3-butanediol

b. 3-methyl-2-hexanol

c. 2-methyl-2-butanol

d. 1,3-cyclopentanediol

13.12 1-octanol

2-octanol

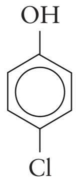
3-octanol

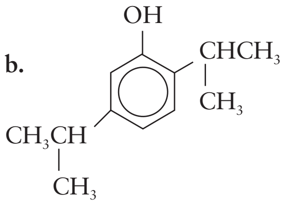
4-octanol

13.14 **a.** 2-ethylphenol or *o*-ethylphenol

b. 2-ethyl-4,6-dimethylphenol

13.16

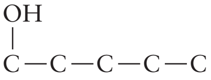
a. 

b. 

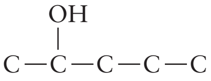
13.18 **a.** tertiary

b. secondary

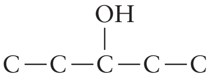
c. secondary

13.20 
$\mathrm{\overset{OH}{C}-C-C-C-C}$

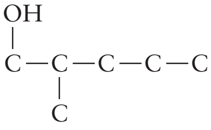
1-pentanol, primary


$\mathrm{C-\overset{OH}{C}-C-C-C}$

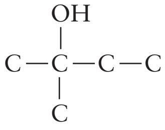
2-pentanol, secondary


$\mathrm{C-C-\overset{OH}{C}-C-C}$

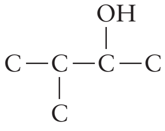
3-pentanol, secondary


$\mathrm{\overset{OH}{C}-\underset{C}{C}-C-C-C}$

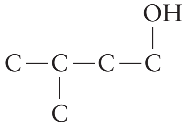
2-methyl-1-butanol, primary


$\mathrm{C-\overset{OH}{\underset{C}{C}}-C-C}$

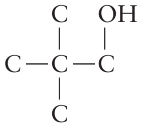
2-methyl-2-butanol, tertiary


$\mathrm{C-\underset{C}{C}-\overset{OH}{C}-C}$

3-methyl-2-butanol, secondary


$\mathrm{C-\underset{C}{C}-C-\overset{OH}{C}}$

3-methyl-1-butanol, primary


$\mathrm{C-\overset{C}{\underset{C}{C}}-\overset{OH}{C}}$

2,2-dimethyl-1-propanol, primary

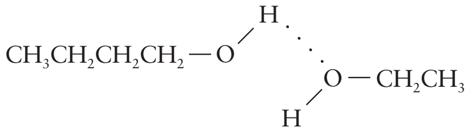
13.22 The boiling points of alcohols are much higher than the boiling points of alkanes with similar molecular weights because alcohols experience hydrogen-bonding intermolecular forces in addition to dispersion forces between the molecules, while alkanes experience dispersion intermolecular forces as their only intermolecular force. Hydrogen bonding is a much stronger intermolecular force and much more energy is required to separate the molecules; therefore, the boiling points of alcohols are much higher than alkanes with similar molecular weights.

13.24 **a.** methanol, ethanol, 1-propanol

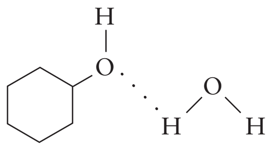
b. butane, 1-propanol, ethylene glycol

13.26 a.	butane or 2-butanol	2-Butanol will be more soluble in water than butane because 2-butanol will hydrogen bond with the water molecules, while nonpolar butane will not.
b.	2-propanol or 2-pentanol	2-Propanol will be more soluble in water than 2-pentanol because while both compounds will hydrogen bond with water, the 2-propanol has a shorter carbon chain and lower molecular weight than the 2-pentanol, which increases water solubility.
c.	2-butanol or 2,3-butanediol	2,3-Butanediol will be more soluble in water than 2-butanol because it contains two hydroxy groups, while the 2-butanol only contains one hydroxy group. The two hydroxy groups increase the hydrogen bonding interactions with water, which increases the solubility of the compound in water.

13.28 a.



b.

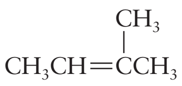


13.30 a. two

b. two

13.32 a. $CH_3CH{=}CHCH_3$

b.

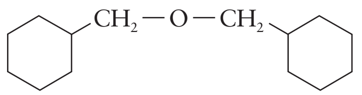


$CH_3CH{=}\overset{CH_3}{\overset{|}{C}}CH_3$

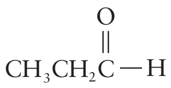
13.34 a. $CH_3{-}O{-}CH_3$

b. $CH_3CH_2CH_2CH_2{-}O{-}CH_2CH_2CH_2CH_3$

c.

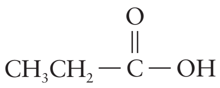


13.36



$CH_3CH_2\overset{O}{\overset{\|}{C}}{-}H$

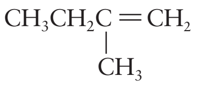
and



$CH_3CH_2{-}\overset{O}{\overset{\|}{C}}{-}OH$

13.38 a. $CH_3CH{=}CHCH_3$

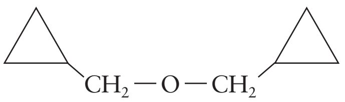
b.



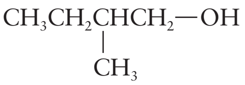
$CH_3CH_2\underset{CH_3}{\underset{|}{C}}{=}CH_2$

c. $CH_3CH_2CH_2{-}O{-}CH_2CH_2CH_3$

d.

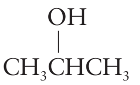


13.40 a.



$CH_3CH_2\underset{CH_3}{\underset{|}{C}}HCH_2{-}OH$

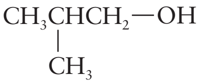
b.



$CH_3\overset{OH}{\overset{|}{C}}HCH_3$ and $CH_3CH_2CH_2{-}OH$

c. $CH_3{-}OH$

d.



$CH_3\underset{CH_3}{\underset{|}{C}}HCH_2{-}OH$

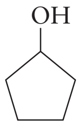
13.42 a. primary

b. secondary

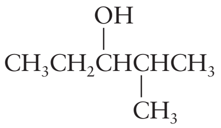
c. primary

d. primary

13.44 a.

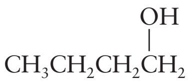


b.



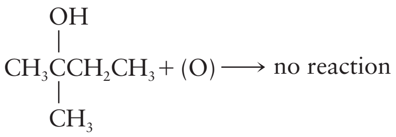
$CH_3CH_2\overset{OH}{\overset{|}{C}}H\underset{CH_3}{\underset{|}{C}}HCH_3$

c.



$CH_3CH_2CH_2\overset{OH}{\overset{|}{C}}H_2$

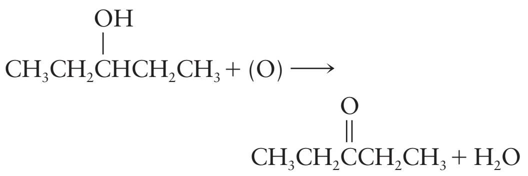
13.46 a.



$CH_3\underset{CH_3}{\underset{|}{\overset{OH}{\overset{|}{C}}}}CH_2CH_3 + (O) \longrightarrow$ no reaction

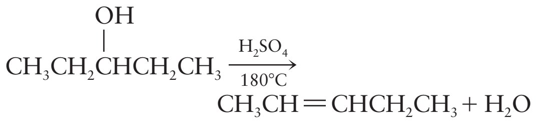
b. $2CH_3CH_2CH_2{-}OH \xrightarrow[140°C]{H_2SO_4} CH_3CH_2CH_2{-}O{-}CH_2CH_2CH_3 + H_2O$

c.

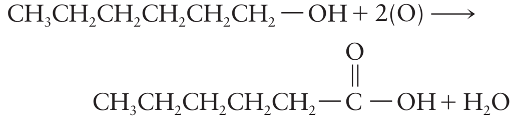


$CH_3CH_2\overset{OH}{\overset{|}{C}}HCH_2CH_3 + (O) \longrightarrow CH_3CH_2\overset{O}{\overset{\|}{C}}CH_2CH_3 + H_2O$

d.

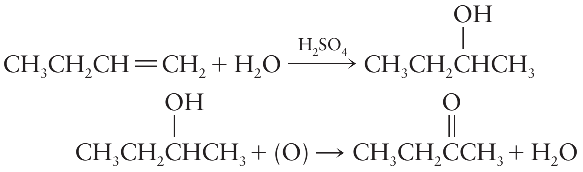


$CH_3CH_2\overset{OH}{\overset{|}{C}}HCH_2CH_3 \xrightarrow[180°C]{H_2SO_4} CH_3CH{=}CHCH_2CH_3 + H_2O$

e. 

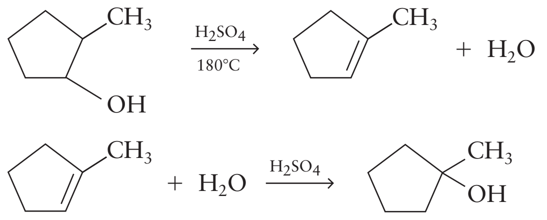
$$CH_3CH_2CH_2CH_2CH_2CH_2-OH + 2(O) \longrightarrow CH_3CH_2CH_2CH_2CH_2-\overset{\overset{O}{\|}}{C}-OH + H_2O$$

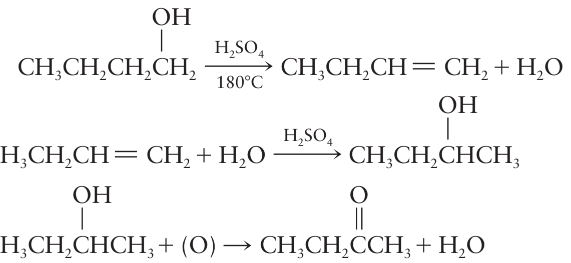
13.48

a. 

$$CH_3CH_2CH=CH_2 + H_2O \xrightarrow{H_2SO_4} CH_3CH_2\overset{\overset{OH}{|}}{C}HCH_3$$

$$CH_3CH_2\overset{\overset{OH}{|}}{C}HCH_3 + (O) \rightarrow CH_3CH_2\overset{\overset{O}{\|}}{C}CH_3 + H_2O$$

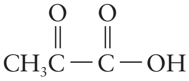
b. 

c. 

$$CH_3CH_2CH_2\overset{\overset{OH}{|}}{C}H_2 \xrightarrow[180^\circ C]{H_2SO_4} CH_3CH_2CH=CH_2 + H_2O$$

$$CH_3CH_2CH=CH_2 + H_2O \xrightarrow{H_2SO_4} CH_3CH_2\overset{\overset{OH}{|}}{C}HCH_3$$

$$CH_3CH_2\overset{\overset{OH}{|}}{C}HCH_3 + (O) \rightarrow CH_3CH_2\overset{\overset{O}{\|}}{C}CH_3 + H_2O$$

13.50 

$$CH_3\overset{\overset{O}{\|}}{C}-\overset{\overset{O}{\|}}{C}-OH$$

13.52 Methanol is used as an automobile fuel and in the preparation of formaldehyde, a starting material for certain plastics.

13.54 a. Glycerol

b. Ethanol

c. Ethylene glycol

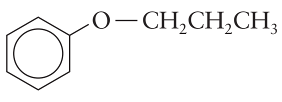
d. Isopropyl alcohol

13.56 a. A vitamin	vitamin E
b. A disinfectant cleaner	*o*-phenylphenol, 2-benzyl-4-chlorophenol

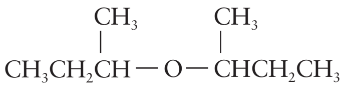
13.58 Both compounds are aromatic but only the structure on the left has the -OH attached to the benzene ring, making it a phenol.

13.60 Structures b and c do not exist because benzene compounds can only have one group attached at each ring position.

13.62 a. $CH_3-O-CH_2CH_3$
ethyl methyl ether

b. 

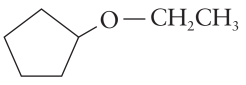
phenyl propyl ether

c. 

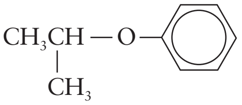
$$CH_3CH_2\overset{\overset{CH_3}{|}}{C}H-O-\overset{\overset{CH_3}{|}}{C}HCH_2CH_3$$

di-*sec*-butyl ether

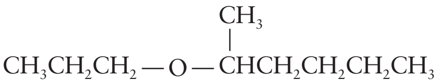
13.64 a. $CH_3-O-CH_2CH_3$
methoxyethane

b. 

ethoxycyclopentane

c. 

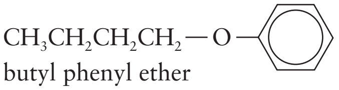
isopropoxybenzene

d. 

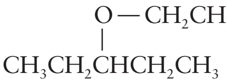
$$CH_3CH_2CH_2-O-\overset{\overset{CH_3}{|}}{C}HCH_2CH_2CH_2CH_3$$

2-propoxyhexane

13.66 a. $CH_3CH_2-O-CH_3$
ethyl methyl ether

b. 

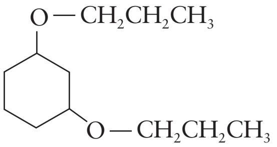
butyl phenyl ether

c. 

$$CH_3CH_2\overset{\overset{O-CH_2CH_3}{|}}{C}HCH_2CH_3$$

3-ethoxypentane

d. $CH_3CH_2CH_2-O-CH_2CH_2CH_3$
dipropyl ether

e. 

1,3-dipropoxycyclohexane

13.68 a. Non-cyclic ether

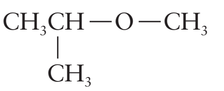
b. Heterocyclic ring ether

c. Non-ether

d. Non-cyclic ether

13.70 $CH_3CH_2CH_2-O-CH_3$
1-methoxypropane

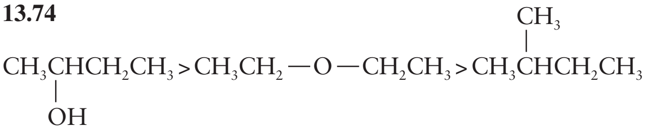
$CH_3CH_2-O-CH_2CH_3$
ethoxyethane



$$CH_3\underset{\underset{CH_3}{|}}{C}H-O-CH_3$$

2-methoxypropane

13.72 Inertness

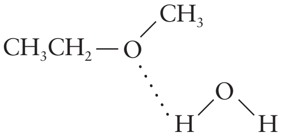
13.74 

$$CH_3\underset{\underset{OH}{|}}{C}HCH_2CH_3 > CH_3CH_2-O-CH_2CH_3 > CH_3\overset{\overset{CH_3}{|}}{C}HCH_2CH_3$$

For compounds of comparable molecular weight. Alcohols are more soluble than ethers, which are more soluble than alkanes.

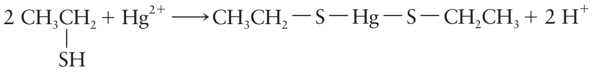
13.76 The order is the same as in the answer to Exercise 13.74. Alcohols have the highest boiling point due to hydrogen bonding. Pure ethers and alkanes exhibit no hydrogen bonding. Ethers are slightly higher boiling than alkanes due to the oxygen atom: alcohol, ether, alkane.

13.78



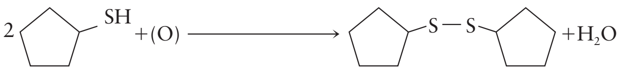
13.80

a.



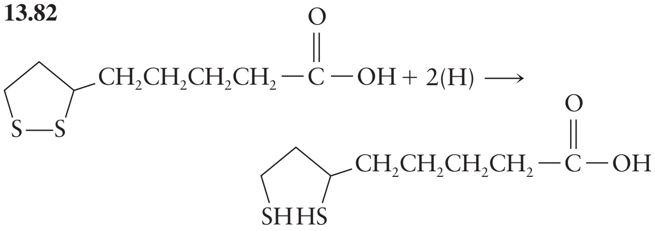
$$2\ \underset{\displaystyle\text{SH}}{\text{CH}_3\text{CH}_2} + \text{Hg}^{2+} \longrightarrow \text{CH}_3\text{CH}_2-\text{S}-\text{Hg}-\text{S}-\text{CH}_2\text{CH}_3 + 2\ \text{H}^+$$

b.



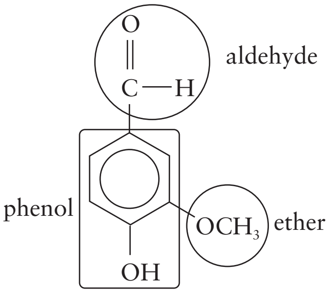
c. $CH_3-S-S-CH_2CH_2CH_3 + 2\ (H) \longrightarrow CH_3-SH + HS\cdots CH_2CH_2CH_3$

13.82



Note: The carboxylic acid functional group will likely also be reduced by the reducing agent to produce a primary alcohol. That reaction has not been introduced at this point in the textbook; therefore, the carboxylic acid functional group was not changed in the solution to this end of chapter exercise.

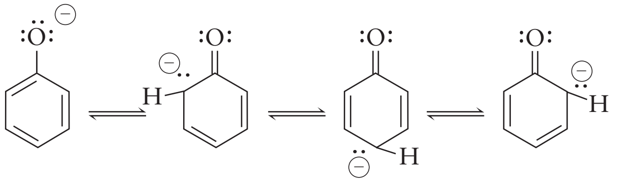
13.84



13.86 aromatic, alkene, aldehyde

13.88 The electronegativity difference between S and H is less than between O and H. This means the S—H bond is less polar, leading to a decreased ability to hydrogen bond. The decrease in hydrogen bonding ability would decrease a thiol's boiling point and water solubility in comparison to the alcohol.

13.90 The negative charge that forms on the oxygen atom when phenol acts as an acid can be delocalized around the ring structure of benzene.



13.92 $R—O—H + X^- \rightarrow R—O^- + HX$

$R—O—H + HA \rightarrow R—OH_2^+ + A^-$

13.94 The three products are:

$CH_3CH_2-O-CH_2CH_3$ diethyl ether

$CH_3CH_2-O-CH_2CH_2CH_3$ ethyl propyl ether

$CH_3CH_2CH_2-O-CH_2CH_2CH_3$ dipropyl ether

Three products form because the two types of alcohol molecules can react with a molecule of the same type to produce either diethyl ether or dipropyl ether or a molecule of a different type to produce ethyl propyl ether.

13.96 Ethanol poses greater risks for fetuses because they are much smaller than adults and their organ systems are still developing, whereas an adult's organ systems are fully developed.

13.98 The -one ending suggests a ketone.

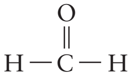
13.100 $2\ CH_3—OH + 3\ O_2 \rightarrow 2\ CO_2 + 4\ H_2O$

13.102 Dye is added to antifreeze before it is sold in stores, so that an antifreeze leak or spill can be easily detected because the color differs from other fluids that may leak from an automobile. It also lessens the chance that antifreeze will be ingested accidentally.

Chapter 14

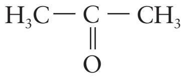
14.2

Simplest aldehyde:



$$\text{H}-\overset{\displaystyle\text{O}}{\overset{\|}{\text{C}}}-\text{H}$$

Simplest ketone:

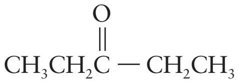


$$\text{H}_3\text{C}-\underset{\displaystyle\text{O}}{\underset{\|}{\text{C}}}-\text{CH}_3$$

14.4 b and d

14.6

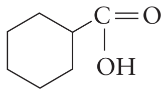
a.



$$\text{CH}_3\text{CH}_2\overset{\displaystyle\text{O}}{\overset{\|}{\text{C}}}-\text{CH}_2\text{CH}_3$$

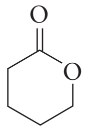
ketone

b.



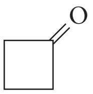
neither (carboxylic acid)

c.



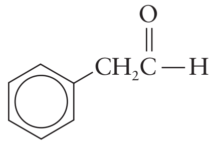
neither (ester)

d.

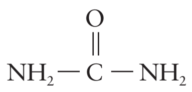


ketone

e.



aldehyde

f. 
$NH_2-\overset{O}{\overset{\|}{C}}-NH_2$ neither (amide)

14.8 **a.** 3-methylbutanal

b. 4-methylheptanal

c. 2-phenylethanal

d. butanal

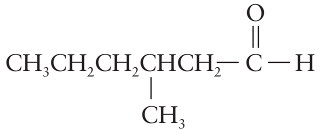
14.10 **a.** 2-pentanone

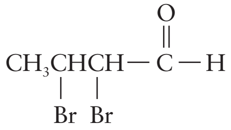
b. 3-pentanone

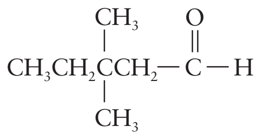
c. 2,4-dimethyl-3-hexanone

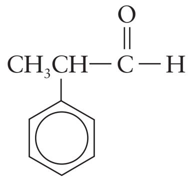
d. 2-methyl-4-phenyl-3-pentanone

14.12

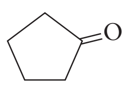
a. 
$CH_3CH_2CH_2\underset{CH_3}{\underset{|}{C}}HCH_2-\overset{O}{\overset{\|}{C}}-H$

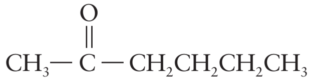
b. 
$CH_3\underset{Br}{\underset{|}{C}}H\underset{Br}{\underset{|}{C}}H-\overset{O}{\overset{\|}{C}}-H$

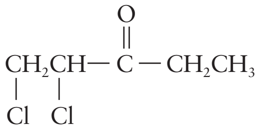
c. 
$CH_3CH_2\underset{CH_3}{\underset{|}{\overset{CH_3}{\overset{|}{C}}}}CH_2-\overset{O}{\overset{\|}{C}}-H$

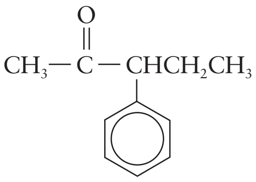
d. 

14.14

a. 

b. 
$CH_3-\overset{O}{\overset{\|}{C}}-CH_2CH_2CH_2CH_3$

c. 
$\underset{Cl}{\underset{|}{C}}H_2\underset{Cl}{\underset{|}{C}}H-\overset{O}{\overset{\|}{C}}-CH_2CH_3$

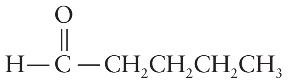
d. 

14.16 2-methyl-3-hexanone

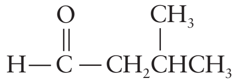
4-methyl-3-hexanone

5-methyl-3-hexanone

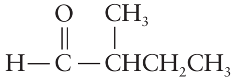
14.18


$H-\overset{O}{\overset{\|}{C}}-CH_2CH_2CH_2CH_3$

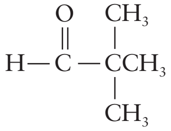
pentanal


$H-\overset{O}{\overset{\|}{C}}-CH_2\overset{CH_3}{\overset{|}{C}}HCH_3$

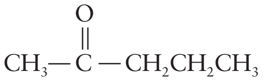
3-methylbutanal


$H-\overset{O}{\overset{\|}{C}}-\overset{CH_3}{\overset{|}{C}}HCH_2CH_3$

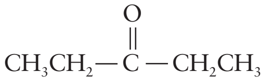
2-methylbutanal


$H-\overset{O}{\overset{\|}{C}}-\underset{CH_3}{\underset{|}{\overset{CH_3}{\overset{|}{C}}}}CH_3$

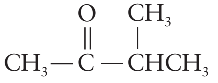
2,2-dimethylpropanal


$CH_3-\overset{O}{\overset{\|}{C}}-CH_2CH_2CH_3$

2-pentanone

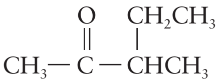

$CH_3CH_2-\overset{O}{\overset{\|}{C}}-CH_2CH_3$

3-pentanone

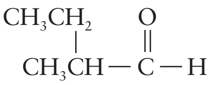

$CH_3-\overset{O}{\overset{\|}{C}}-\overset{CH_3}{\overset{|}{C}}HCH_3$

3-methyl-2-butanone

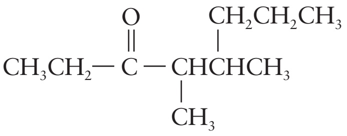
14.20 **a.** Incorrect = 3-ethyl-2-butanone
correct = 3-methy-2-pentanone


$CH_3-\overset{O}{\overset{\|}{C}}-\overset{CH_2CH_3}{\overset{|}{C}}HCH_3$

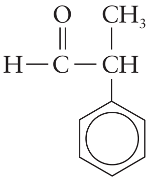
b. Incorrect = 2-ethyl-propanal
correct = 2-methylbutanal


$CH_3\overset{CH_3CH_2}{\overset{|}{C}}H-\overset{O}{\overset{\|}{C}}-H$

c. Incorrect = 4-methyl-5-propyl-3-hexanone
correct = 4,5-dimethyl-3-octanone


$CH_3CH_2-\overset{O}{\overset{\|}{C}}-\underset{CH_3}{\underset{|}{C}}H\overset{CH_2CH_2CH_3}{\overset{|}{C}}HCH_3$

d. Incorrect = 2-methyl-2-phenylethanal
correct = 2-phenylpropanal



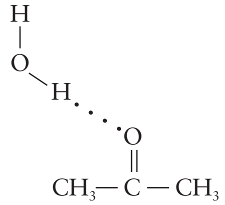
14.22 Hydrogen bonding does not occur between molecules of aldehydes or ketones because aldehydes and ketones do not contain an oxygen atom bonded directly to a hydrogen atom.

14.24 The boiling point of propanal is 49°C because it experiences only dipolar forces. The boiling point of propanol is 97°C because it experiences hydrogen bonding forces. The stronger intermolecular forces of propanol cause it to have a higher boiling point than propanal.

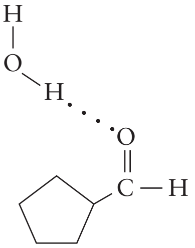
14.26 c < b < a

14.28 Ethanal should be more water soluble because the hydrophobic portion of the molecule is smaller than the hydrophobic portion of hexanal.

14.30 **a.**



b.

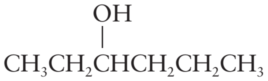


14.32 b < c < a

14.34 The alcohol will have the higher melting point because of hydrogen bonding. Menthol is a solid, and menthone is a liquid.

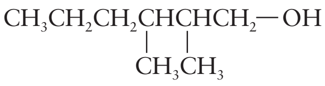
14.36

a.



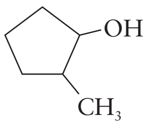
$$CH_3CH_2\overset{\overset{OH}{|}}{C}HCH_2CH_2CH_3$$

b.



$$CH_3CH_2CH_2\underset{\underset{CH_3}{|}}{C}H\underset{\underset{CH_3}{|}}{C}HCH_2-OH$$

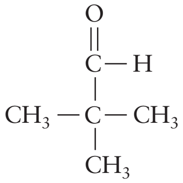
c.



d. $CH_3CH_2CH_2CH_2-OH$

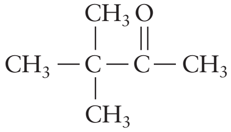
14.38

a.



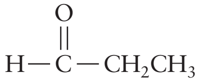
$$CH_3-\underset{\underset{CH_3}{|}}{\overset{\overset{\overset{O}{\|}}{C-H}}{\overset{|}{C}}}-CH_3$$

b.



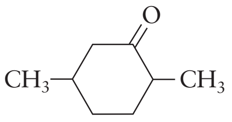
$$CH_3-\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}}-\overset{\overset{O}{\|}}{C}-CH_3$$

c.



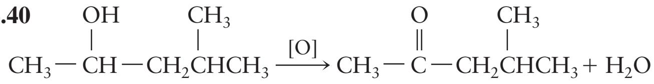
$$H-\overset{\overset{O}{\|}}{C}-CH_2CH_3$$

d.



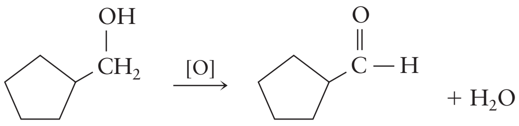
14.40

a.

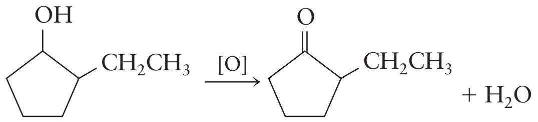


$$CH_3-\overset{\overset{OH}{|}}{C}H-CH_2\overset{\overset{CH_3}{|}}{C}HCH_3 \xrightarrow{[O]} CH_3-\overset{\overset{O}{\|}}{C}-CH_2\overset{\overset{CH_3}{|}}{C}HCH_3 + H_2O$$

b.



c.



14.42 a, d

14.44 b, c, d

14.46 b

14.48 b, d

14.50 **a.** Neither

b. Hemiacetal

c. Neither

d. Hemiketal

14.52 **a.** Ketal

b. Acetal

c. Neither

14.54 **a.** Ketal

b. None of these

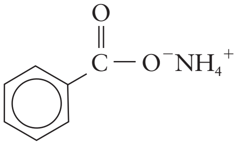
c. Hemiacetal

14.56 They are unstable, splitting into an alcohol and an aldehyde.

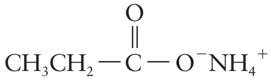
14.58 The formation of a silver precipitate or mirror.

14.60

b.



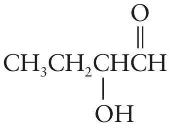
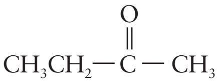
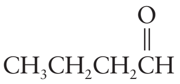
d.



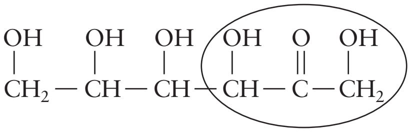
$$CH_3CH_2-\overset{\overset{O}{\|}}{C}-O^-NH_4^+$$

14.62 b

14.64

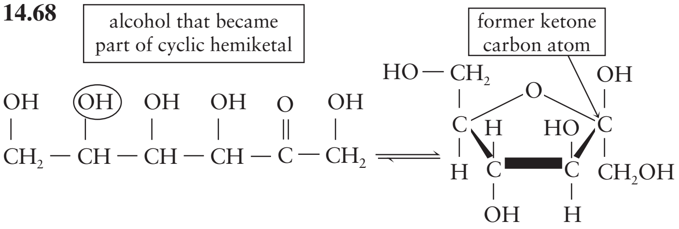
	Tollens' Reagent	**Benedict's Reagent**	
Bottle A	A dark precipitate forms	A red-orange precipitate forms	 $CH_3CH_2\underset{\underset{OH}{\vert}}{C}H\overset{\overset{O}{\Vert}}{C}H$
Bottle B	No reaction	No reaction	 $CH_3CH_2-\overset{\overset{O}{\Vert}}{C}-CH_3$
Bottle C	A dark precipitate and slight mirror form	No reaction	 $CH_3CH_2CH_2\overset{\overset{O}{\Vert}}{C}H$

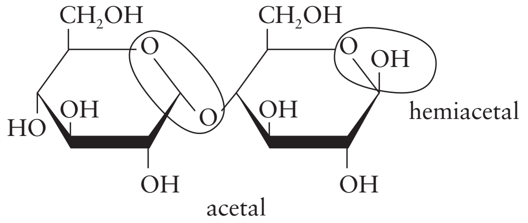
14.66



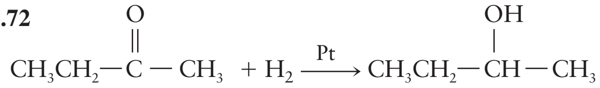
$$\overset{\overset{OH}{|}}{CH_2}-\overset{\overset{OH}{|}}{CH}-\overset{\overset{OH}{|}}{CH}-\overset{\overset{OH}{|}}{CH}-\overset{\overset{O}{\|}}{C}-\overset{\overset{OH}{|}}{CH_2}$$

(a ketone with adjacent alcohol groups)

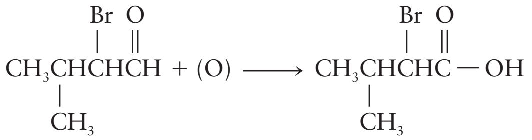
14.68 
alcohol that became part of cyclic hemiketal
former ketone carbon atom

14.70 

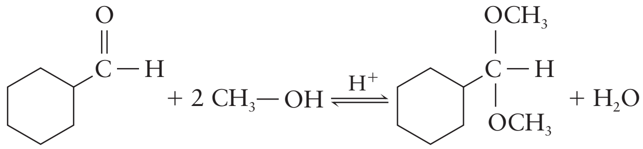
14.72

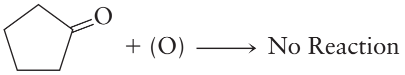
a. 

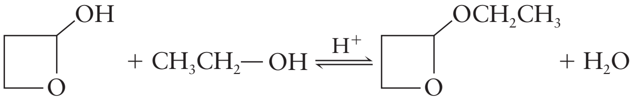
$$CH_3CH_2-\overset{O}{\overset{\|}{C}}-CH_3 + H_2 \xrightarrow{Pt} CH_3CH_2-\overset{OH}{\overset{|}{CH}}-CH_3$$

b. 

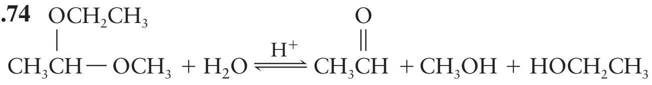
$$CH_3\underset{CH_3}{\underset{|}{C}}H\overset{Br}{\overset{|}{C}}H\overset{O}{\overset{\|}{C}}H + (O) \longrightarrow CH_3\underset{CH_3}{\underset{|}{C}}H\overset{Br}{\overset{|}{C}}H\overset{O}{\overset{\|}{C}}-OH$$

c. 

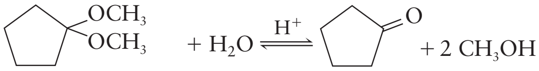
d. 

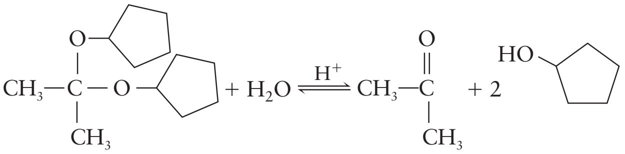
e. 

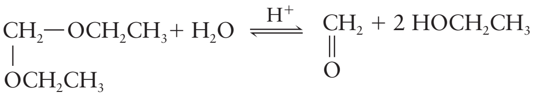
14.74

a. 

$$CH_3\overset{OCH_2CH_3}{\overset{|}{C}}H-OCH_3 + H_2O \overset{H^+}{\rightleftharpoons} CH_3\overset{O}{\overset{\|}{C}}H + CH_3OH + HOCH_2CH_3$$

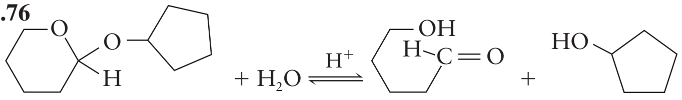
b. 

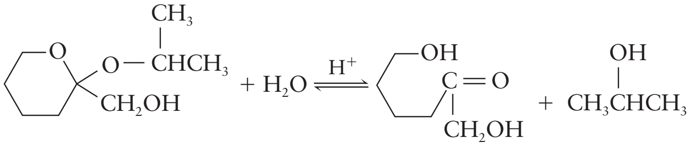
c. 

d. 

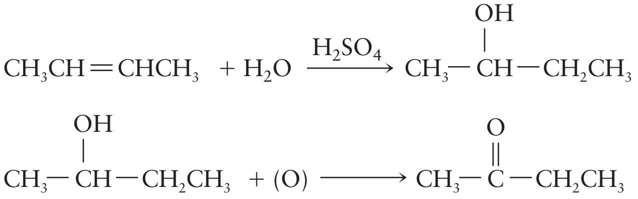
$$\underset{OCH_2CH_3}{\underset{|}{CH_2}}-OCH_2CH_3 + H_2O \overset{H^+}{\rightleftharpoons} \underset{O}{\underset{\|}{CH_2}} + 2\,HOCH_2CH_3$$

14.76

a. 

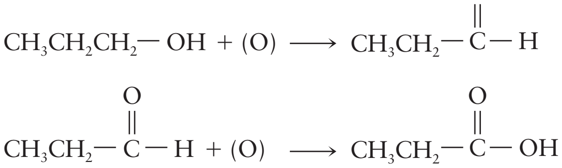
b. 

14.78

a. 

$$CH_3CH{=}CHCH_3 + H_2O \xrightarrow{H_2SO_4} CH_3-\overset{OH}{\overset{|}{CH}}-CH_2CH_3$$

$$CH_3-\overset{OH}{\overset{|}{CH}}-CH_2CH_3 + (O) \longrightarrow CH_3-\overset{O}{\overset{\|}{C}}-CH_2CH_3$$

b. 

$$CH_3CH_2CH_2-OH + (O) \longrightarrow CH_3CH_2-\overset{O}{\overset{\|}{C}}-H$$

$$CH_3CH_2-\overset{O}{\overset{\|}{C}}-H + (O) \longrightarrow CH_3CH_2-\overset{O}{\overset{\|}{C}}-OH$$

14.80 Formaldehyde is the most important aldehyde. In 37% aqueous solution, it kills microorganisms and is effective in sterilizing surgical instruments; it is also used to embalm cadavers. It is a key industrial chemical in the production of plastics, such as Bakelite® and Formica®.

Acetone is the most important ketone. It is useful as a solvent.

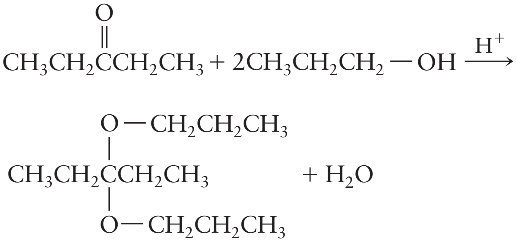
14.82 **a.** citral

b. camphor

c. menthone

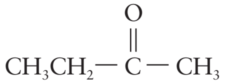
d. biacetyl

14.84 461 g

14.86 

$$CH_3CH_2\overset{O}{\overset{\|}{C}}CH_2CH_3 + 2CH_3CH_2CH_2-OH \xrightarrow{H^+} CH_3CH_2\overset{O-CH_2CH_2CH_3}{\overset{|}{\underset{O-CH_2CH_2CH_3}{\underset{|}{C}}}}CH_2CH_3 + H_2O$$

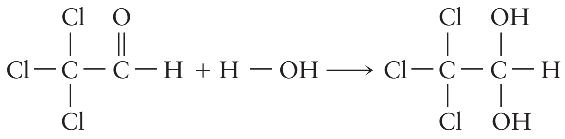
14.88 Butanone is the preferable IUPAC name for this structure because 2-butanone is repetitive in nature. The only possible location of the carbonyl carbon atom in the four-carbon parent chain is carbon 2; therefore, butanone is a sufficient name for this structure.



$$CH_3CH_2-\overset{O}{\overset{\|}{C}}-CH_3$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

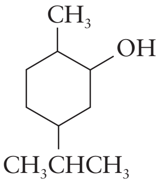
14.90



$$\mathrm{Cl-\overset{\overset{Cl}{|}}{\underset{\underset{Cl}{|}}{C}}-\overset{\overset{O}{\|}}{C}-H + H-OH \longrightarrow Cl-\overset{\overset{Cl}{|}}{\underset{\underset{Cl}{|}}{C}}-\overset{\overset{OH}{|}}{\underset{\underset{OH}{|}}{C}}-H}$$

trichloroacetaldehyde chloral hydrate

14.92



14.94 The chemical structures of the aldehydes should be the same; however, the vanilla extract from an orchid is likely to contain other natural compounds in addition to the vanillin, which may enhance the flavor of the vanilla extract. Imitation vanilla extract is typically less expensive.

14.96 $C_3H_6O + 4\ O_2 \rightarrow 3\ CO_2 + 3\ H_2O$

Chapter 15

15.2 b, c, and d

15.4 Carboxylic acids with more than ten carbon atoms are called fatty acids. They were originally produced by the saponification of fats.

15.6 Lactic acid

15.8 **a.** Pentanoic acid

b. 3-methylpentanoic acid

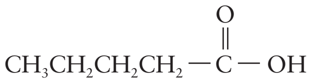
c. 4-phenylhexanoic acid

d. 2,4-dimethylbenzoic acid

e. 3-ethyl-5-methylhexanoic acid

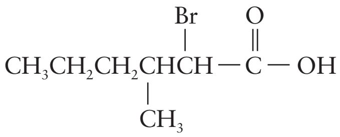
15.10

a.



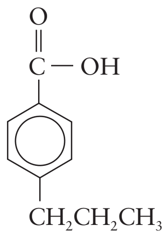
$$\mathrm{CH_3CH_2CH_2CH_2-\overset{\overset{O}{\|}}{C}-OH}$$

b.



$$\mathrm{CH_3CH_2CH_2\underset{\underset{CH_3}{|}}{C}H\overset{\overset{Br}{|}}{C}H-\overset{\overset{O}{\|}}{C}-OH}$$

c.



15.12 **a.** Acetic acid because it forms dimers

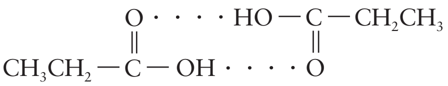
b. Propanoic acid because it forms dimers

c. Butyric acid because it has a higher molecular weight

15.14 **b.** hexane < **a.** pentanal < **c.** 1-pentanol < **d.** butanoic acid

The order of increasing boiling point is alkane, aldehyde, alcohol, carboxylic acid. All of these compounds experience approximately equal dispersion forces since their molar masses are similar. Hexane experiences only dispersion forces, which are weaker than the combination of dispersion forces and dipolar forces experienced by pentanal. Both 1-pentanol and butanoic acid form hydrogen bonds, but butanoic acid has two sites for hydrogen bonding per molecule compared to only one site per molecule for 1-pentanol. This results in a greater degree of hydrogen bonding and a higher boiling point.

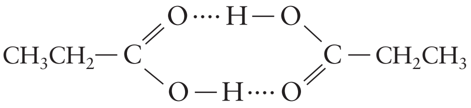
15.16



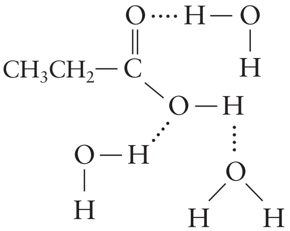
$$\begin{array}{l} \mathrm{\phantom{CH_3CH_2-{}}O\cdots\cdots HO-C-CH_2CH_3}\\ \mathrm{\phantom{CH_3CH_2-{}}\|\phantom{\cdots\cdots HO-{}}\|}\\ \mathrm{CH_3CH_2-C-OH\cdots\cdots O}\end{array}$$

15.18

a.



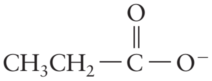
b.



15.20 The carboxyl group is hydrophilic; the carbon chain is hydrophobic.

15.22 pentane < ethoxyethane < 1-butanol < propanoic acid

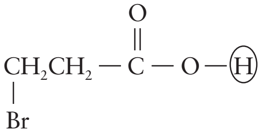
15.24



$$\mathrm{CH_3CH_2-\overset{\overset{O}{\|}}{C}-O^-}$$

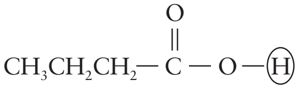
15.26

a.



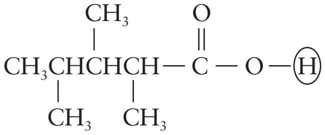
$$\mathrm{\underset{\underset{Br}{|}}{C}H_2CH_2-\overset{\overset{O}{\|}}{C}-O-\text{Ⓗ}}$$

b.



$$\mathrm{CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-O-\text{Ⓗ}}$$

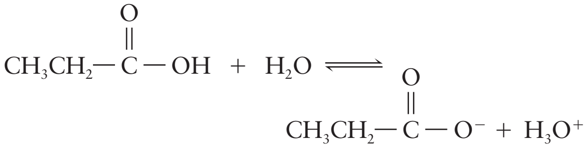
c.



$$\mathrm{CH_3\underset{\underset{CH_3}{|}}{C}H\overset{\overset{CH_3}{|}}{C}H\underset{\underset{CH_3}{|}}{C}H-\overset{\overset{O}{\|}}{C}-O-\text{Ⓗ}}$$

15.28 The most important chemical property of carboxylic acids is the acidic behavior implied by their name.

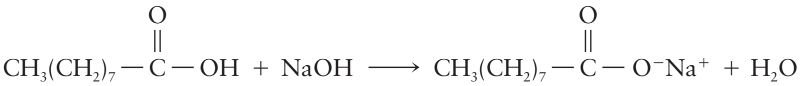
15.30

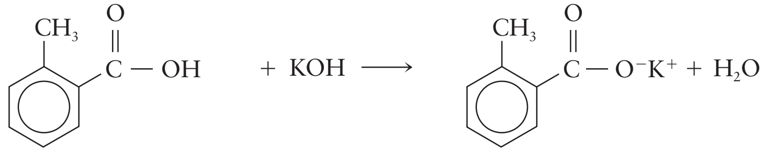


$$\mathrm{CH_3CH_2-\overset{\overset{O}{\|}}{C}-OH + H_2O \rightleftharpoons CH_3CH_2-\overset{\overset{O}{\|}}{C}-O^- + H_3O^+}$$

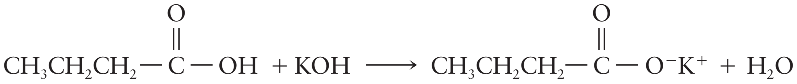
At a pH of 12, the propanoate ion is the predominant form because the OH^- ions remove the H_3O^+ ions from solution and shift the equilibrium to the right. At a pH of 2, the propanoic acid is the predominant form because the excess H_3O^+ ions shift the equilibrium to the left.

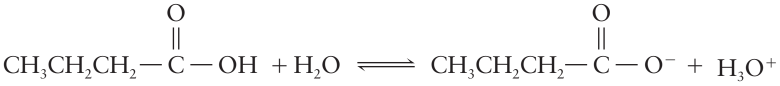
15.32

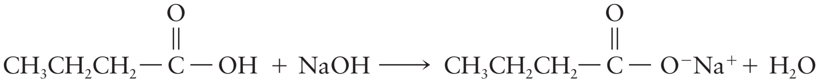
a. 
$CH_3(CH_2)_7-\overset{O}{\overset{\|}{C}}-OH + NaOH \longrightarrow CH_3(CH_2)_7-\overset{O}{\overset{\|}{C}}-O^-Na^+ + H_2O$

b. 

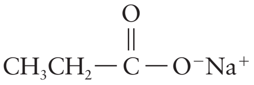
15.34

a. 
$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-OH + KOH \longrightarrow CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-O^-K^+ + H_2O$

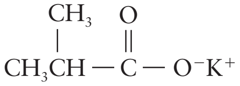
b. 
$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-OH + H_2O \rightleftharpoons CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-O^- + H_3O^+$

c. 
$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-OH + NaOH \longrightarrow CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-O^-Na^+ + H_2O$

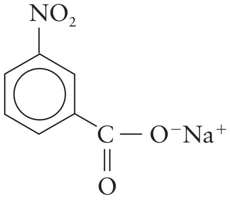
15.36

a. 
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-O^-Na^+$

sodium propanoate

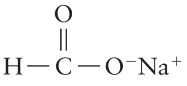
b. 
$CH_3\underset{}{\overset{CH_3}{\overset{|}{C}}}H-\overset{O}{\overset{\|}{C}}-O^-K^+$

potassium
2-methylpropanoate

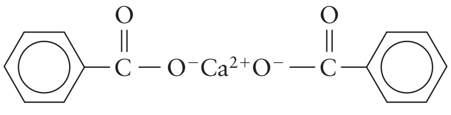
c. 

sodium
m-nitrobenzoate

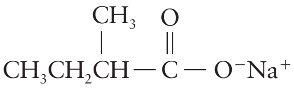
15.38

a. 
$H-\overset{O}{\overset{\|}{C}}-O^-Na^+$

sodium formate

b. 

calcium benzoate

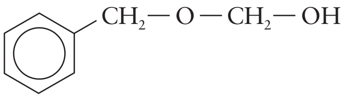
c. 
$CH_3CH_2\overset{CH_3}{\overset{|}{C}}H-\overset{O}{\overset{\|}{C}}-O^-Na^+$

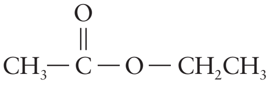
sodium 2-methylbutanoate

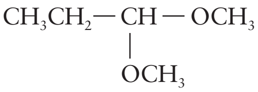
15.40	**a.** The sodium salt of valeric acid	sodium valerate
	b. The magnesium salt of lactic acid	magnesium lactate
	c. The potassium salt of citric acid	potassium citrate

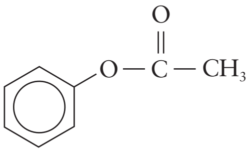
15.42 **a.** sodium stearate
b. calcium propanoate
c. citric acid and sodium citrate
d. sodium benzoate

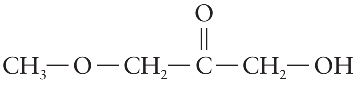
15.44

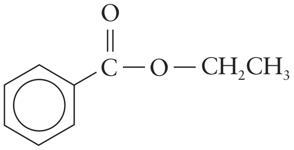
a. 
not an ester (ether, alcohol)

b. 
$CH_3-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3$
ester

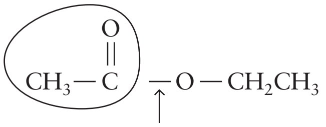
c. 
$CH_3CH_2-\underset{OCH_3}{\underset{|}{C}}H-OCH_3$
not an ester (acetal)

d. 
ester

e. 
$CH_3-O-CH_2-\overset{O}{\overset{\|}{C}}-CH_2-OH$
not an ester (ether, ketone, alcohol)

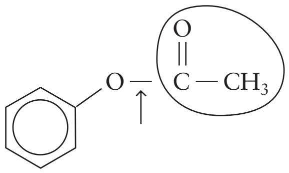
f. 
ester

15.46 **b.**

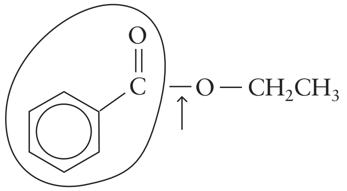


$CH_3-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3$

d.

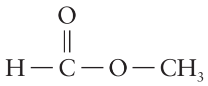


f.



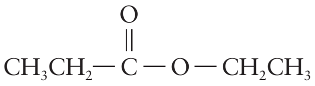
15.48

a.



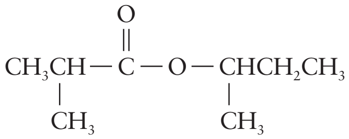
$H-\overset{O}{\overset{\|}{C}}-O-CH_3$

b.



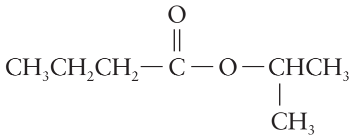
$CH_3CH_2-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3$

c.



$\underset{CH_3}{\underset{|}{CH_3CH}}-\overset{O}{\overset{\|}{C}}-O-\underset{CH_3}{\underset{|}{CHCH_2CH_3}}$

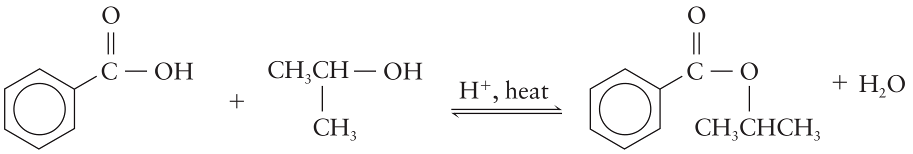
d.



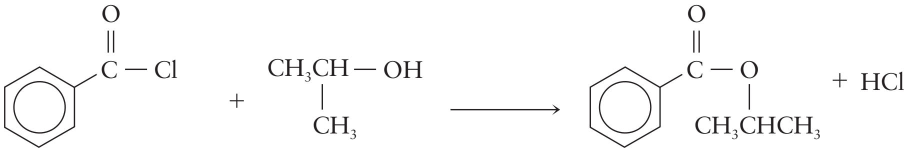
$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-O-\underset{CH_3}{\underset{|}{CHCH_3}}$

15.50

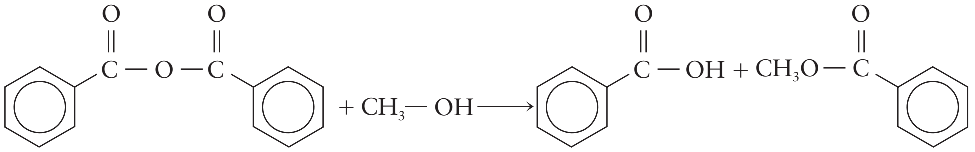
a.



b.

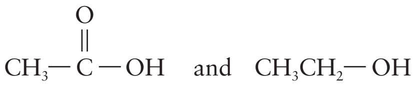


c.



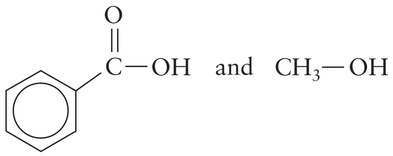
15.52

a.

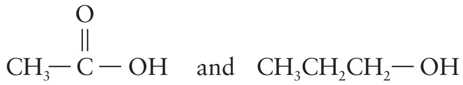


$CH_3-\overset{O}{\overset{\|}{C}}-OH$ and CH_3CH_2-OH

b.

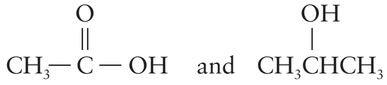


c.



$CH_3-\overset{O}{\overset{\|}{C}}-OH$ and $CH_3CH_2CH_2-OH$

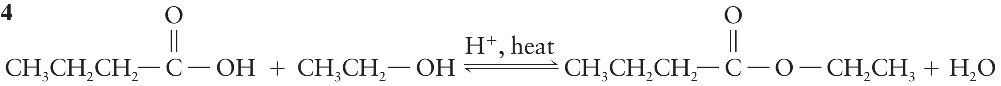
d.



$CH_3-\overset{O}{\overset{\|}{C}}-OH$ and $\overset{OH}{\overset{|}{CH_3CHCH_3}}$

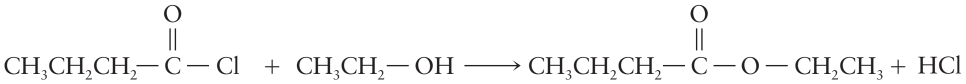
15.54

a.



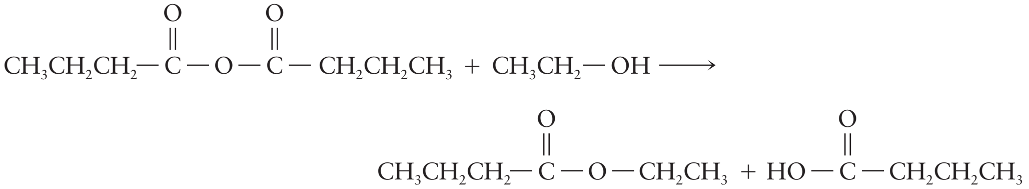
$$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-OH + CH_3CH_2-OH \xrightleftharpoons{H^+,\ heat} CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3 + H_2O$$

b.



$$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-Cl + CH_3CH_2-OH \longrightarrow CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3 + HCl$$

c.

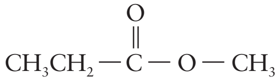


$$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-O-\overset{O}{\overset{\|}{C}}-CH_2CH_2CH_3 + CH_3CH_2-OH \longrightarrow$$

$$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3 + HO-\overset{O}{\overset{\|}{C}}-CH_2CH_2CH_3$$

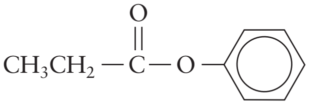
15.56

a.

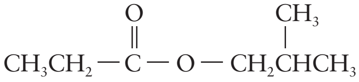


$$CH_3CH_2-\overset{O}{\overset{\|}{C}}-O-CH_3$$

b.

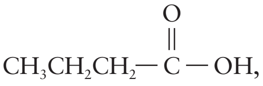


c.



$$CH_3CH_2-\overset{O}{\overset{\|}{C}}-O-CH_2\overset{CH_3}{\overset{|}{C}}HCH_3$$

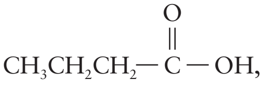
15.58 **a.** Pineapple flavoring



$$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-OH,$$

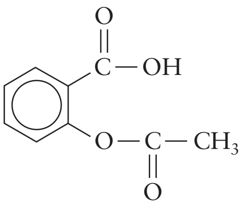
$HO-CH_2CH_2CH_2CH_3$

b. Apple flavoring

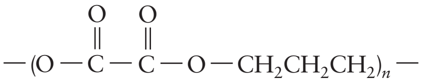


$$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-OH,$$ $HO-CH_3$

15.60



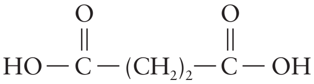
15.62



$$-(O-\overset{O}{\overset{\|}{C}}-\overset{O}{\overset{\|}{C}}-O-CH_2CH_2CH_2)_n-$$

15.64

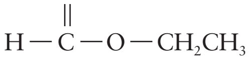
$HO-CH_2CH_2CH_2-OH$ and



$$HO-\overset{O}{\overset{\|}{C}}-(CH_2)_2-\overset{O}{\overset{\|}{C}}-OH$$

15.66

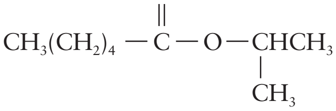
a.



$$H-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3$$

ethyl formate

b.

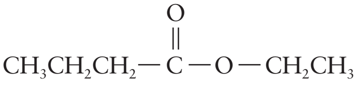


$$CH_3(CH_2)_4-\overset{O}{\overset{\|}{C}}-O-\underset{CH_3}{\underset{|}{C}}HCH_3$$

isopropyl caproate

15.68

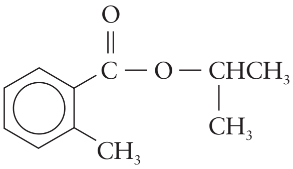
a.



$$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3$$

ethyl butanoate

b.



isopropyl *o*-methylbenzoate

15.70 **a.** Methyl propionate

b. Propyl acetate

15.72 **a.** Methyl butanoate

b. Propyl propanoate

15.74 **a.** Ethyl ethanoate

b. Propyl ethanoate

c. Butyl ethanoate

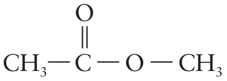
15.76 **a.** Methyl propionate

b. Methyl butyrate

c. Methyl lactate

15.78

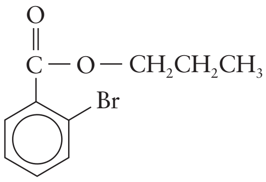
a.



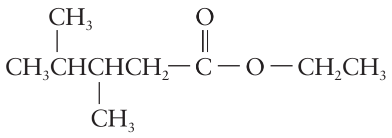
$$CH_3-\overset{O}{\overset{\|}{C}}-O-CH_3$$

methyl ethanoate

b.



propyl 2-bromobenzoate

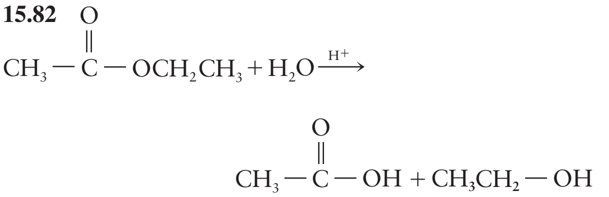
c. 

$$\mathrm{CH_3\underset{CH_3}{C}H\overset{CH_3}{C}HCH_2-\overset{O}{\overset{\|}{C}}-O-CH_2CH_3}$$

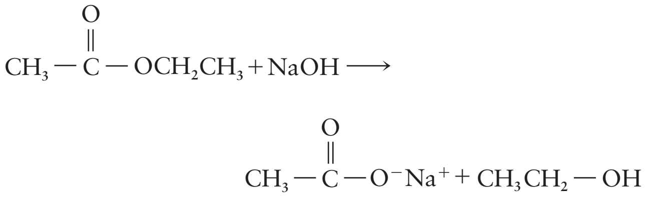
ethyl 3,4-dimethylpentanoate

15.80 Ester hydrolysis is the reversible reaction in which water reacts with an ester in the presence of an acid catalyst to produce a carboxylic acid and an alcohol.

Saponification is the basic cleavage of an ester linkage that produces the salt of a carboxylic acid and an alcohol.

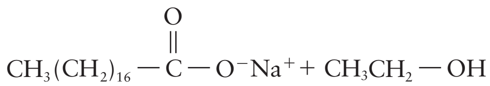
15.82 

$$\mathrm{CH_3-\overset{O}{\overset{\|}{C}}-OCH_2CH_3+H_2O\xrightarrow{H^+}CH_3-\overset{O}{\overset{\|}{C}}-OH+CH_3CH_2-OH}$$

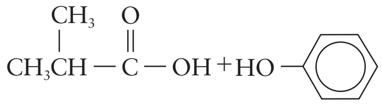


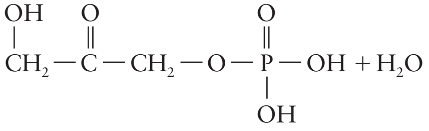
$$\mathrm{CH_3-\overset{O}{\overset{\|}{C}}-OCH_2CH_3+NaOH\longrightarrow CH_3-\overset{O}{\overset{\|}{C}}-O^-Na^++CH_3CH_2-OH}$$

15.84

a. 

$$\mathrm{CH_3(CH_2)_{16}-\overset{O}{\overset{\|}{C}}-O^-Na^++CH_3CH_2-OH}$$

b. 

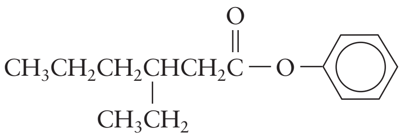
15.86 

$$\mathrm{\overset{OH}{\overset{|}{C}}H_2-\overset{O}{\overset{\|}{C}}-CH_2-O-\overset{O}{\overset{\|}{\underset{OH}{\underset{|}{P}}}}-OH+H_2O}$$

15.88 When $NaHCO_3$ reacts with an acid, it forms CO_2 gas, water, and a salt:

$$RCO_2H + NaHCO_3 \rightarrow RCO_2^-Na^+ + CO_2 + H_2O$$

There would be no reaction with an alcohol. Therefore, the presence of effervescence ("bubbling") indicates an acid.

15.90 

phenyl 3-ethylhexanoate

15.92 **1.** Use an excessive quantity of ethanol.

2. Remove the water as it is being formed.

15.94 Polarity: d > a > b > c

Boiling Points: c < b < a < d

Chapter 16

16.2 a, b, c

16.4 R—NH_2 (primary), R_2NH (secondary), and R_3N (tertiary).

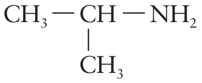
16.6 **a.** Secondary

b. Tertiary

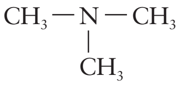
c. Primary

d. Secondary

16.8 (1) $CH_3-CH_2-CH_2-NH_2$ primary

(2)  $\mathrm{CH_3-\underset{CH_3}{\underset{|}{C}}H-NH_2}$ primary

(3) $CH_3-CH_2-NH-CH_3$ secondary

(4)  $\mathrm{CH_3-\underset{CH_3}{\underset{|}{N}}-CH_3}$ tertiary

16.10 **a.** Methylphenylamine

b. Diethylamine

c. Ethylisopropylamine

16.12 **a.** Cyclohexanamine

b. *N*-ethylcyclohexanamine

c. 2-butanamine

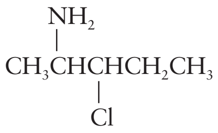
16.14 **a.** *N*-methylethanamine

b. 3-methyl-1-pentanamine

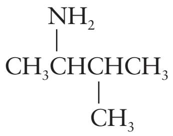
c. *N,N*-diethylethanamine

d. Cyclohexanamine

16.16

a. 

$$\mathrm{CH_3\overset{NH_2}{\overset{|}{C}}H\underset{Cl}{\underset{|}{C}}HCH_2CH_3}$$

b. 

$$\mathrm{CH_3\overset{NH_2}{\overset{|}{C}}H\underset{CH_3}{\underset{|}{C}}HCH_3}$$

c. $CH_3CH_2-NH_2$

16.18 **a.** *N*-isopropylaniline

b. *N,N*-diethylaniline

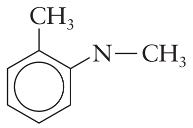
16.20 **a.** *N*-ethyl-*N*-methyl-1-propanamine or ethylmethylpropylamine

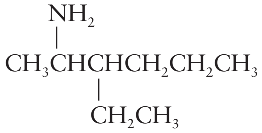
b. *N*-ethylaniline or ethylphenylamine

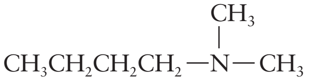
c. 2-methyl-3-pentanamine

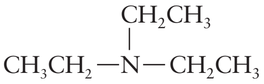
d. 2-chloroaniline

16.22

a. 

b. 
$CH_3\overset{\overset{NH_2}{|}}{C}H\underset{\underset{CH_2CH_3}{|}}{C}HCH_2CH_2CH_3$

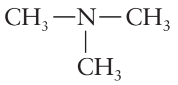
c. 
$CH_3CH_2CH_2CH_2-\overset{\overset{CH_3}{|}}{N}-CH_3$

d. 
$CH_3CH_2-\overset{\overset{CH_2CH_3}{|}}{N}-CH_2CH_3$

16.24 The boiling points of amines are lower than those of the corresponding alcohols because the hydrogen bonds formed between nitrogen and hydrogen are weaker than the hydrogen bonds formed between oxygen and hydrogen.

16.26 Molecules of butanamine can form hydrogen bonds. The increased attraction between molecules gives rise to a higher boiling point.

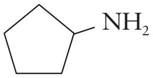
16.28 c < b < a

16.30 b. 
$CH_3-\underset{\underset{CH_3}{|}}{N}-CH_3$ < **a.** $CH_3CH_2CH_2-NH_2$ <

c. $CH_3CH_2CH_2-OH$

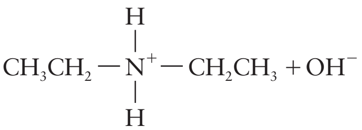
Since the molecular weights of these three compounds are comparable, they experience comparable dispersion forces. The order of their boiling points is determined by the nature of the other intermolecular forces they experience. Tertiary amines have the lowest boiling point because they are unable to form hydrogen bonds with other tertiary amines. Primary amines have an intermediate boiling point because they are capable of forming hydrogen bonds between their molecules but these hydrogen bonds are not as strong as the hydrogen bonds between the molecules of primary alcohols, which have the highest boiling point.

16.32 b < c < a

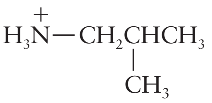
16.34 a. 
because as a primary amine, it can exhibit greater hydrogen bonding with water molecules.

b. $CH_3CH_2-NH-CH_3$ because it has a lower molecular weight and fewer hydrophobic carbon atoms.

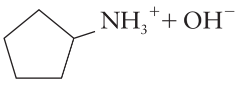
16.36 $CH_3CH_2-NH-CH_2CH_3 + H_2O \rightleftharpoons$

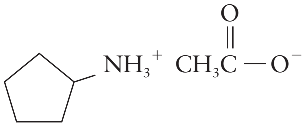

$CH_3CH_2-\underset{\underset{H}{|}}{\overset{\overset{H}{|}}{N^+}}-CH_2CH_3 + OH^-$

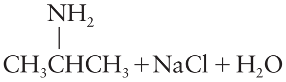
16.38 a. OH^-

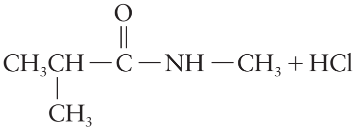
b. 
$H_3\overset{+}{N}-CH_2\underset{\underset{CH_3}{|}}{C}HCH_3$

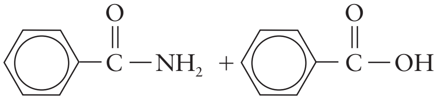
16.40 **a.** $CH_3CH_2CH_2CH_2-NH_3^+Cl^-$

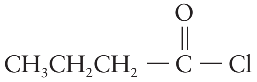
b. 

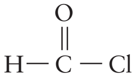
c. 

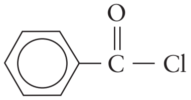
d. 
$CH_3\overset{\overset{NH_2}{|}}{C}HCH_3 + NaCl + H_2O$

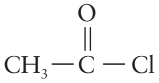
e. 
$CH_3\underset{\underset{CH_3}{|}}{C}H-\overset{\overset{O}{\|}}{C}-NH-CH_3 + HCl$

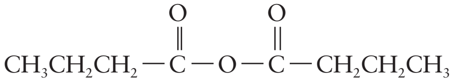
f. 

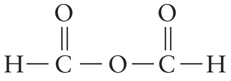
16.42 a. 
$CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-Cl$

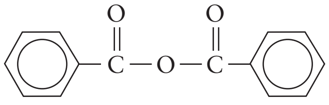
b. 
$H-\overset{\overset{O}{\|}}{C}-Cl$

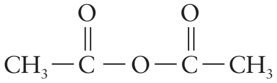
c. 

d. 
$CH_3-\overset{\overset{O}{\|}}{C}-Cl$

16.44 a. 
$CH_3CH_2CH_2-\overset{\overset{O}{\|}}{C}-O-\overset{\overset{O}{\|}}{C}-CH_2CH_2CH_3$

b. 
$H-\overset{\overset{O}{\|}}{C}-O-\overset{\overset{O}{\|}}{C}-H$

c. 

d. 
$CH_3-\overset{\overset{O}{\|}}{C}-O-\overset{\overset{O}{\|}}{C}-CH_3$

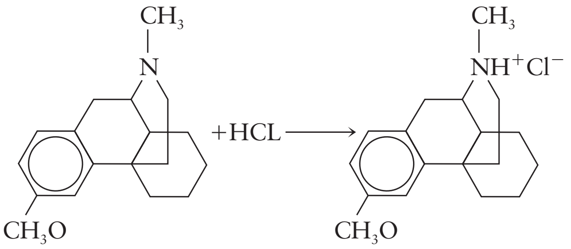
16.46 a. Amine salt

b. Amine salt

c. Quaternary ammonium salt

16.48 The structure of a quaternary ammonium salt differs from the structure of a salt of a tertiary amine because the nitrogen atom of a quaternary ammonium salt is bonded directly to four carbon atoms, while the nitrogen atom of a salt of a tertiary amine is bonded directly to three carbon atoms and one hydrogen atom.

16.50



16.52 Polyester: a dicarboxylic acid chloride and a diol Polyamide: a dicarboxylic acid chloride and a diamine

16.54 **a.** NaOH
- **b.** NH_3
- **c.** HCl

16.56 Synapse

16.58 Norepinephrine and serotonin

16.60 Norepinephrine, serotonin, acetylcholine, and dopamine

16.62 Epinephrine is used clinically in local anesthetics to constrict blood vessels in the area of injection.

16.64 Plants

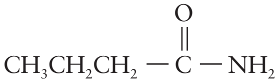
16.66 **a.** Caffeine
- **b.** Atropine
- **c.** Nicotine
- **d.** Codeine
- **e.** Quinine
- **f.** Morphine

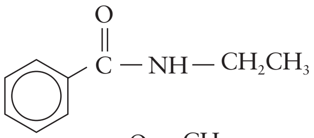
16.68 c, d

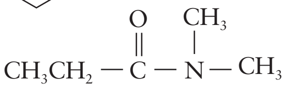
16.70 **a.** *N*-methylbutanamide
- **b.** *N*,*N*-dimethylethanamide
- **c.** 2-methylbenzamide or *o*-methylbenzamide
- **d.** 2-methylbutanamide

16.72 **a.** propanamide
- **b.** *N*-butylethanamide
- **c.** *N*-methyl-3-methylbutanamide
- **d.** *N*,*N*-dimethylpropanamide

16.74

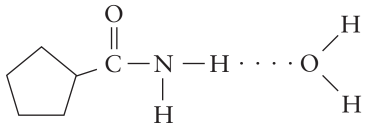
a.

$CH_3CH_2CH_2-\overset{O}{\overset{\|}{C}}-NH_2$

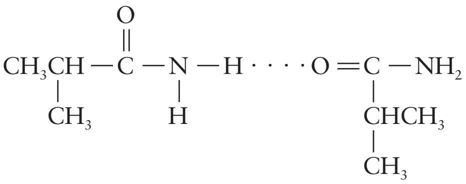
b.


c.

$CH_3CH_2-\overset{O}{\overset{\|}{C}}-\overset{CH_3}{\overset{|}{N}}-CH_3$

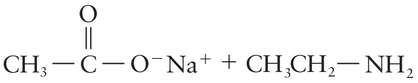
16.76 *N*-ethylpropanamide would have the higher boiling point because as a secondary amine, it can exhibit greater hydrogen bonding than a tertiary amine.

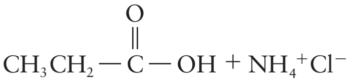
16.78

a.


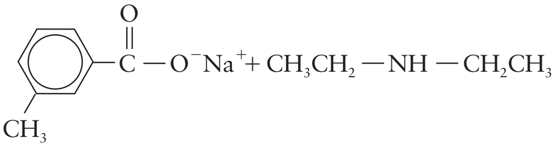
b.

$\underset{CH_3}{\underset{|}{CH_3CH}}-\overset{O}{\overset{\|}{C}}-\underset{H}{\underset{|}{N}}-H\cdots\cdots O=\underset{\underset{CH_3}{\underset{|}{CHCH_3}}}{\underset{|}{C}}-NH_2$

16.80

a.

$CH_3-\overset{O}{\overset{\|}{C}}-O^-Na^+ + CH_3CH_2-NH_2$

b.

$CH_3CH_2-\overset{O}{\overset{\|}{C}}-OH + NH_4^+Cl^-$

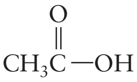
16.82



16.84 **a.** Saturated
- **b.** One $C{=}C$ bond
- **c.** Two $C{=}C$ bonds

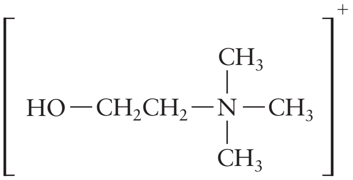
16.86 $Na^+\ {}^-O_2C(CH_2)_4CO_2^-\ Na^+$ and $NH_2(CH_2)_6NH_2$

16.88


$CH_3\overset{O}{\overset{\|}{C}}-OH$

acetic acid

and


$\left[HO-CH_2CH_2-\underset{CH_3}{\underset{|}{\overset{CH_3}{\overset{|}{N}}}}-CH_3\right]^+$

choline

16.90 Neurotransmitter is a substance that acts as a chemical bridge in nerve impulse transmission between nerve cells.

16.92 d

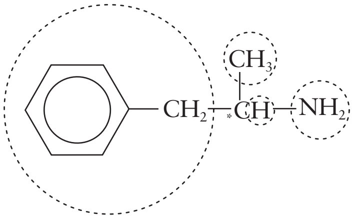
Chapter 17

17.2 **a.** A structural material in plants
- **b.** An energy source in our diet
- **c.** A stored form of energy in animals
- **d.** A stored form of energy in plants

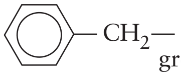
17.4 **a.** disaccharide, carbohydrate
- **b.** monosaccharide, carbohydrate
- **c.** polysaccharide, carbohydrate
- **d.** polysaccharide, carbohydrate

17.6 Carbohydrates are polyhydroxy aldehydes and ketones, or substances that yield such compounds on hydrolysis. In other words, carbohydrates contain alcohol, aldehyde, and ketone functional groups or will contain those functional groups upon hydrolysis.

17.8



CH₃
CH₂
*
CH
NH₂

The chiral carbon atom is marked with an asterisk. The four attached groups are:
(1) a hydrogen atom,
(2) an amino group,
(3) a methyl group, and
(4) a  group.

17.10 **a.** Yes

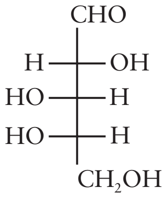
b. Yes

c. No

d. No

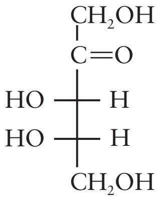
17.12 2 chiral carbons, 4 stereoisomers

17.14 **a.**



CHO
H
OH
HO
H
HO
H
CH₂OH

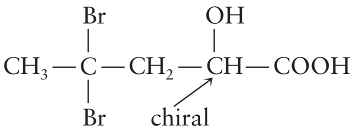
b.



CH₂OH
C=O
HO
H
HO
H
CH₂OH

17.16

a.

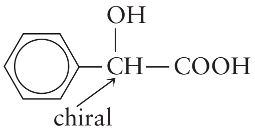


$CH_3-\underset{Br}{\overset{Br}{C}}-CH_2-\overset{OH}{CH}-COOH$

chiral

1 chiral carbon atom; a pair of enantiomers

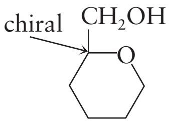
b.



OH
CH—COOH
chiral

1 chiral carbon atom; stereisomers; a pair of enantiomers

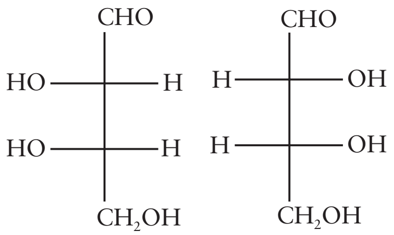
c.



chiral
CH₂OH
O

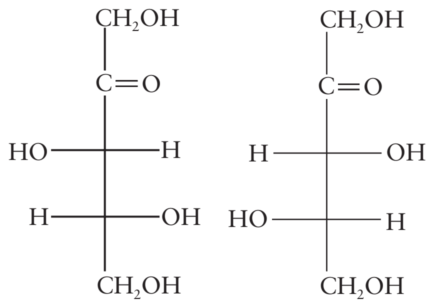
1 chiral carbon atom; stereisomers; a pair of enantiomers

17.18



CHO
HO
H
HO
H
CH₂OH
CHO
H
OH
H
OH
CH₂OH

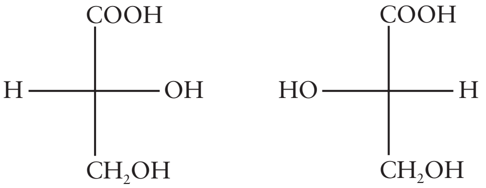
a. L-form D-form



CH₂OH
C=O
HO
H
H
OH
CH₂OH
CH₂OH
C=O
H
OH
HO
H
CH₂OH

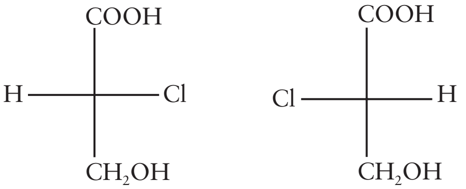
b. D-form L-form

17.20



COOH
H
OH
CH₂OH
COOH
HO
H
CH₂OH

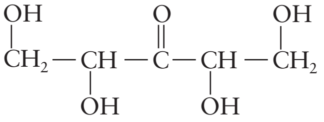
a. D-form L-form



COOH
H
Cl
CH₂OH
COOH
Cl
H
CH₂OH

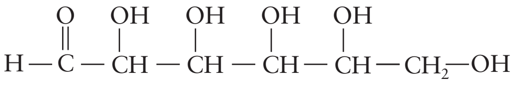
b. D-form L-form

17.22



$\overset{OH}{CH_2}-\underset{OH}{CH}-\overset{O}{\overset{\|}{C}}-\underset{OH}{CH}-\overset{OH}{CH_2}$

a. 2 chiral carbon atoms; 4 stereoisomers



$H-\overset{O}{\overset{\|}{C}}-\overset{OH}{CH}-\overset{OH}{CH}-\overset{OH}{CH}-\overset{OH}{CH}-CH_2-OH$

b. 4 chiral carbon atoms; 16 stereoisomers

17.24 Aldoheptoses contain 5 chiral carbon atoms; therefore, 32 possible stereoisomers exist. Sixteen of these stereoisomers are D form and 16 are L form.

17.26 The study of chiral molecules is important in biochemistry because living organisms consist largely of chiral substances. The stereochemistry of a biological compound plays a key role in determining which receptors with which it will interact and enzymes will be able to catalyze its reactions, as well as what its physiological effect on an organism will be.

17.28 **a.** same

b. same

c. rotate plane-polarized light in different directions

d. same

17.30 **a.** Ketone

b. Aldose

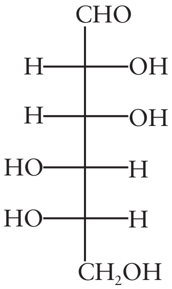
c. Aldose

17.32 **a.** Pentose

b. Hexose

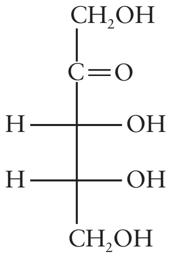
c. Tetrose

17.34 **a.**


CHO
H
OH
H
OH
HO
H
HO
H
CH₂OH

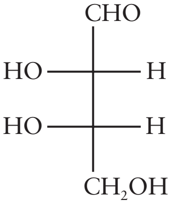
Aldohexose

b.


CH₂OH
C=O
H
OH
H
OH
CH₂OH

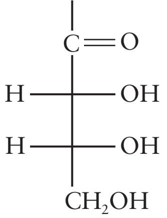
Ketopentose

17.36 **a.**


CHO
HO
H
HO
H
CH₂OH

An aldotetrose must have:
(1)—CHO at the top, (2) 4 total carbon atoms, and (3)—CH_2OH at the bottom of the structure. This aldotetrose has the L configuration.

b.

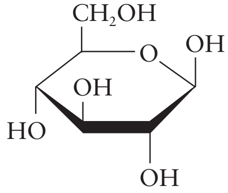

CH₂OH
C=O
H
OH
H
OH
CH₂OH

A ketopentose must have:
(1) a—CH_2OH bonded to a carbonyl carbon atom at the top, (2) 5 total carbon atoms, and (3) a—CH_2OH at the bottom of the structure. This ketopentose has the D configuration.

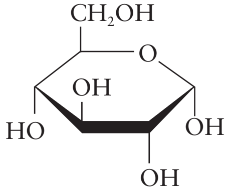
17.38 Monosaccharides are soluble in water because they have many hydroxy groups and are able to hydrogen bond to the water.

17.40

a.

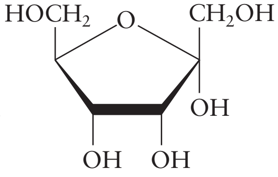

CH₂OH
O
OH
OH
HO
OH

β form

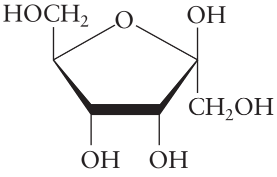

CH₂OH
O
OH
HO
OH
OH

α form

b.

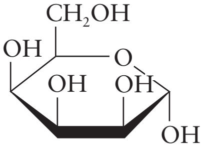

HOCH₂
O
CH₂OH
OH
OH
OH

α form

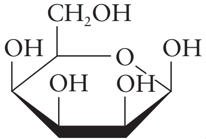

HOCH₂
O
OH
CH₂OH
OH
OH

β form

17.42


CH₂OH
OH
O
OH
OH
OH

α-talose


CH₂OH
OH
O
OH
OH
OH

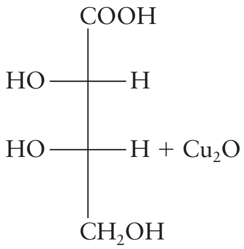
β-talose

17.44 A pyranose ring refers to a carbohydrate that has a six-membered ring containing an oxygen atom. A furanose ring refers to a carbohydrate that has a five-membered ring containing an oxygen atom.

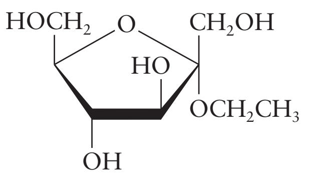
17.46 The cyclic compound β-D-galactose can react with Cu^{2+} and be classified as a reducing sugar because as it undergoes mutarotation in solution, the ring opens, an aldehyde is formed, and the compound can react with Benedict's reagent, which is an oxidizing agent.

17.48 All will give a positive Benedict's test.

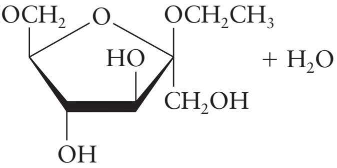
17.50 **a.**


COOH
HO
H
HO
H + Cu₂O
CH₂OH

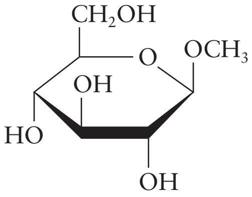
b.



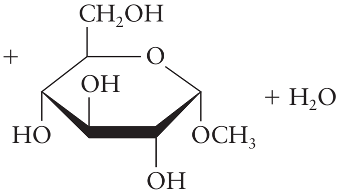
+



c.

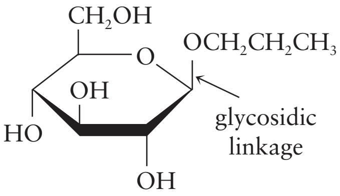


+

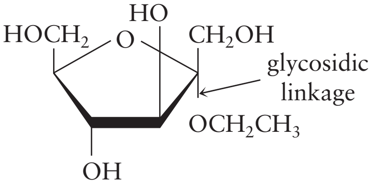


17.52

a.



b.



17.54 a. $CH_3CH_2CH_2OH$

b. CH_3CH_2OH

17.56 D-glucose can be injected directly into the bloodstream to serve as an energy source because glucose is the sugar transported by the blood to body tissues to satisfy energy requirements. Glucose has high solubility in aqueous solutions; it dissolves readily in water and in blood; therefore, it poses no risks of toxicity itself and will not form dangerous solid occlusions in the blood vessels.

17.58 b. Fructose is a ketohexose.

17.60 a. The natural sources of glucose are honey and fruits, as well as sucrose which is a disaccharide containing glucose.

b. The natural source of fructose is fruit.

c. The natural source of galactose is milk, which contains the disaccharide lactose.

17.62 Glucose is a component of sucrose, maltose, and lactose.

17.64 a. Sucrose

b. Maltose

c. Lactose

d. Maltose

e. Sucrose

f. Sucrose

17.66 The glucose ring opens at the hemiacetal group, exposing an aldehyde group that then reacts with the Cu^{2+} of the Benedict's reagent.

17.68 a. Glucose, fructose

b. Glucose, glucose

c. Galactose, glucose

17.70 a. $1 \rightarrow 4$

b. $1 \rightarrow 6$

c. $1 \rightarrow 4$

17.72 a. β

b. α

c. β

17.74 a. Yes

b. Yes

c. Yes

17.76 Perform a Benedict's test. Sucrose is not a reducing sugar, but honey contains reducing sugars.

17.78 The right ring in lactose has a hemiacetal group that can open to form the aldehyde and alcohol; hence, it is a reducing sugar. Sucrose has no hemiacetal bonds, so it can't reduce Cu^{2+}.

17.80 a. Galactose and glucose

b. Yes; there is a hemiacetal on the glucose ring.

c. $\alpha(1 \rightarrow 6)$

17.82 a. Amylose, cellulose

b. Amylose

c. Cellulose

d. Glycogen

17.84 Both are comprised of glucose units with $\alpha(1 \longrightarrow 4)$ and $\alpha(1 \longrightarrow 6)$ linkages. Glycogen contains more branching.

Both are comprised of glucose units linked $\alpha(1 \longrightarrow 4)$. Amylopectin has $\alpha(1 \longrightarrow 6)$ linkages, which amylose lacks. Amylose is a straight chain, while amylopectin is branched.

Both are comprised of linear chains of glucose units, linked $1 \longrightarrow 4$. In amylose, the linkage is alpha, while in cellulose it is beta.

17.86 The boiling point of the glucose solution will be higher because the molarity of the solution is higher.

17.88 Glucose and fructose are formed in equal amounts (52.6 g). The extra mass comes from the water needed for hydrolysis.

17.90 As hydrolysis occurred, the molarity of the solution would increase, causing an increase in osmotic pressure, and the solution level in the tube would rise.

17.92
$$\frac{2.80 \times 10^5 \text{ U}}{1 \text{ molecule starch}}\left(\frac{1 \text{ molecule linked glucose}}{171 \text{ U linked glucose}}\right)$$
$$= 1.64 \times 10^3 \text{ glucose molecules}$$

Note: The molecular mass of glucose is 180 U, but when glucose links together to form a molecule of starch, 1 molecule of water (18.0 U) is lost for every two glucose units or 0.5 molecules of water per glucose unit; therefore, the molecular mass of a linked glucose unit is 180 − 9.0 = 171 U.

17.94 Aspartame (Nutrasweet) contains calories and yet is used in diet drinks. A drink can contain aspartame as a sweetener and yet be low in calories because the amount needed to sweeten a diet drink is so small that very few calories are added to the drink.

17.96 Foods that would be expected to give a positive starch test include bread, crackers, pasta, and rice.

17.98 The longevity of paper would be reduced because of the ease with which amylose (starch) is hydrolyzed.

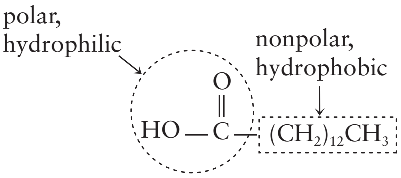
Chapter 18

18.2 Energy storage, structural components, some hormones

18.4
- **a.** Nonsaponifiable
- **b.** Saponifiable
- **c.** Saponifiable
- **d.** Saponifiable

18.6 a and c

18.8


polar,
hydrophilic
nonpolar,
hydrophobic
O
HO—C—
(CH2)12CH3

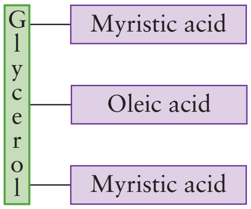
18.10 A micelle is a spherical cluster of fatty acid ions in which the nonpolar chains extend toward the interior of the structure away from water and the polar carboxylate groups face outward in contact with the water. The nonpolar chains in a micelle are held together by weak dispersion forces.

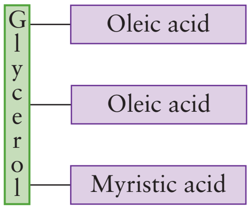
18.14 Unsaturated fatty acids have a bent structure that prevents the molecules from packing as tightly as saturated fatty acids.

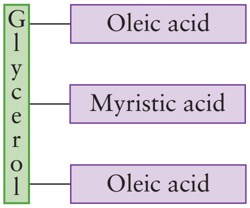
18.16
- **a.** Saturated
- **b.** Polyunsaturated, 4 double bonds, omega-6 fatty acid
- **c.** Monounsaturated
- **d.** Polyunsaturated, 6 double bonds, omega-3 fatty acid

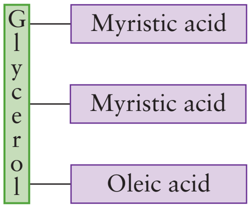
18.18 Fats and oils are both triglycerides (esters). Fats are solid at room temperature; oils are liquid at room temperature. Fats tend to have more saturated fatty acids, whereas oils tend to have more unsaturated fatty acids.

18.20

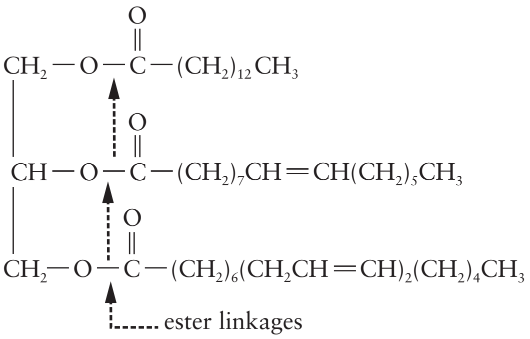

Glycerol
Myristic acid
Oleic acid
Myristic acid


Glycerol
Oleic acid
Oleic acid
Myristic acid


Glycerol
Oleic acid
Myristic acid
Oleic acid


Glycerol
Myristic acid
Myristic acid
Oleic acid

18.22

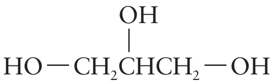

CH2—O—C—(CH2)12CH3
CH—O—C—(CH2)7CH=CH(CH2)5CH3
CH2—O—C—(CH2)6(CH2CH=CH)2(CH2)4CH3
ester linkages

18.24 Triglycerides from animal sources (other than fish) tend to have more saturated fatty acids. Triglycerides from plants or fish tend to have more unsaturated fatty acids.

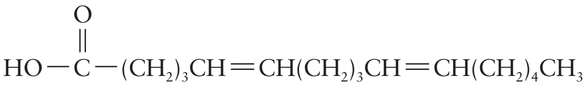
18.26 Triglyceride B

18.28 Hydrogenation

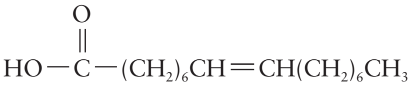
18.30



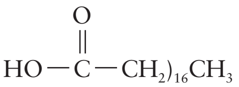
$HO-CH_2\overset{OH}{\overset{|}{C}}HCH_2-OH$



$HO-\overset{O}{\overset{\|}{C}}-(CH_2)_3CH=CH(CH_2)_3CH=CH(CH_2)_4CH_3$

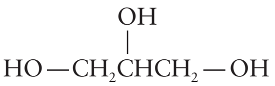


$HO-\overset{O}{\overset{\|}{C}}-(CH_2)_6CH=CH(CH_2)_6CH_3$

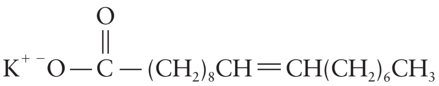


$HO-\overset{O}{\overset{\|}{C}}-CH_2)_{16}CH_3$

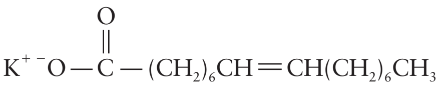
18.32



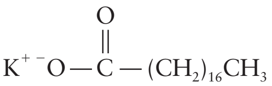
$HO-CH_2\overset{OH}{\overset{|}{C}}HCH_2-OH$



$K^+\ ^-O-\overset{O}{\overset{\|}{C}}-(CH_2)_8CH=CH(CH_2)_6CH_3$

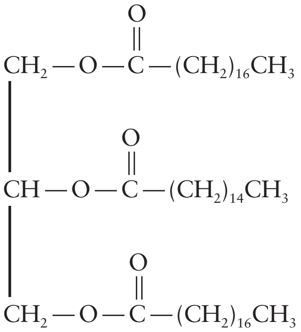


$K^+\ ^-O-\overset{O}{\overset{\|}{C}}-(CH_2)_6CH=CH(CH_2)_6CH_3$



$K^+\ ^-O-\overset{O}{\overset{\|}{C}}-(CH_2)_{16}CH_3$

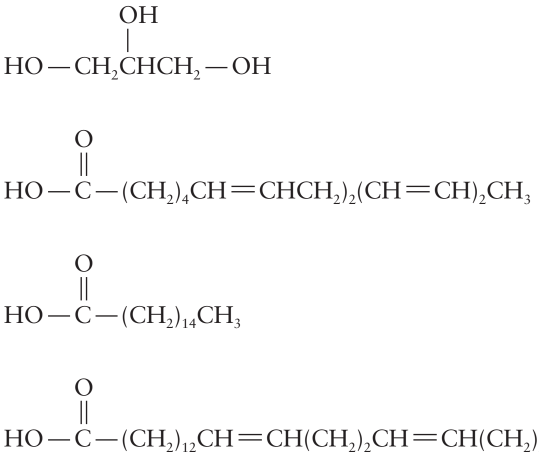
18.34


CH2—O—C—(CH2)16CH3
CH—O—C—(CH2)14CH3
CH2—O—C—(CH2)16CH3

18.36 Two

18.38

a.



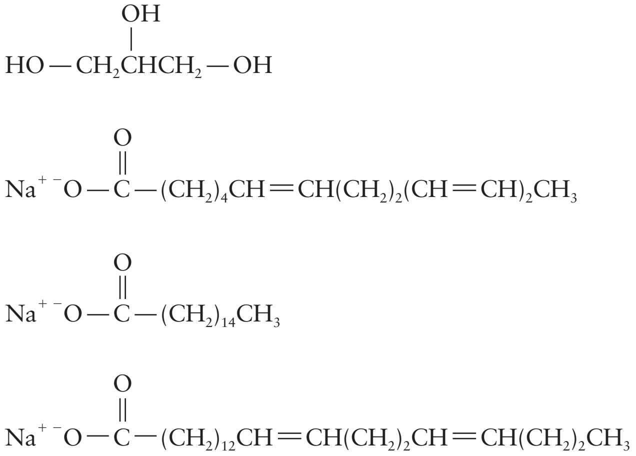
$$\mathrm{HO{-}CH_2\overset{OH}{C}HCH_2{-}OH}$$

$$\mathrm{HO{-}\overset{O}{C}{-}(CH_2)_4CH{=}CHCH_2)_2(CH{=}CH)_2CH_3}$$

$$\mathrm{HO{-}\overset{O}{C}{-}(CH_2)_{14}CH_3}$$

$$\mathrm{HO{-}\overset{O}{C}{-}(CH_2)_{12}CH{=}CH(CH_2)_2CH{=}CH(CH_2)_2CH_3}$$

b.



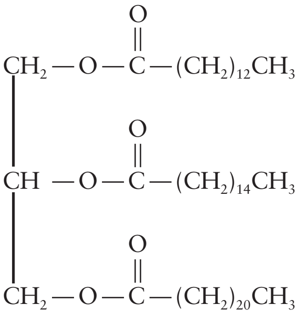
$$\mathrm{HO{-}CH_2\overset{OH}{C}HCH_2{-}OH}$$

$$\mathrm{Na^{+}\,{}^{-}O{-}\overset{O}{C}{-}(CH_2)_4CH{=}CH(CH_2)_2(CH{=}CH)_2CH_3}$$

$$\mathrm{Na^{+}\,{}^{-}O{-}\overset{O}{C}{-}(CH_2)_{14}CH_3}$$

$$\mathrm{Na^{+}\,{}^{-}O{-}\overset{O}{C}{-}(CH_2)_{12}CH{=}CH(CH_2)_2CH{=}CH(CH_2)_2CH_3}$$

c.



$$\begin{array}{l} \mathrm{CH_2{-}O{-}\overset{O}{C}{-}(CH_2)_{12}CH_3} \\ | \\ \mathrm{CH\ {-}O{-}\overset{O}{C}{-}(CH_2)_{14}CH_3} \\ | \\ \mathrm{CH_2{-}O{-}\overset{O}{C}{-}(CH_2)_{20}CH_3} \end{array}$$

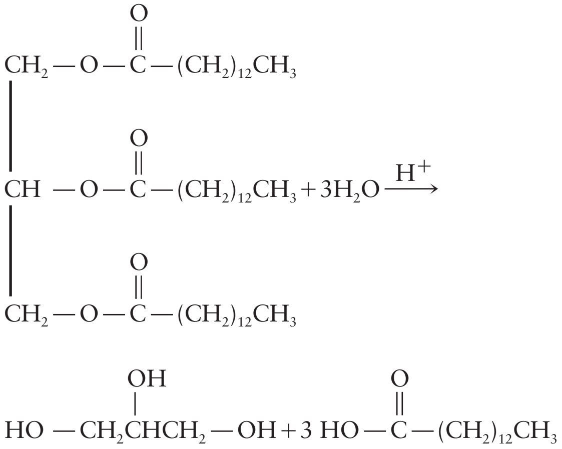
18.40 **a.** Acid hydrolysis of a fat → glycerol + 3 fatty acids (more saturated than unsaturated)

b. Acid hydrolysis of an oil → glycerol + 3 fatty acids (more unsaturated than saturated)

c. Saponification of a fat → glycerol + 3 salts of fatty acids (soaps)

d. Saponification of an oil → glycerol + 3 salts of fatty acids (soaps)

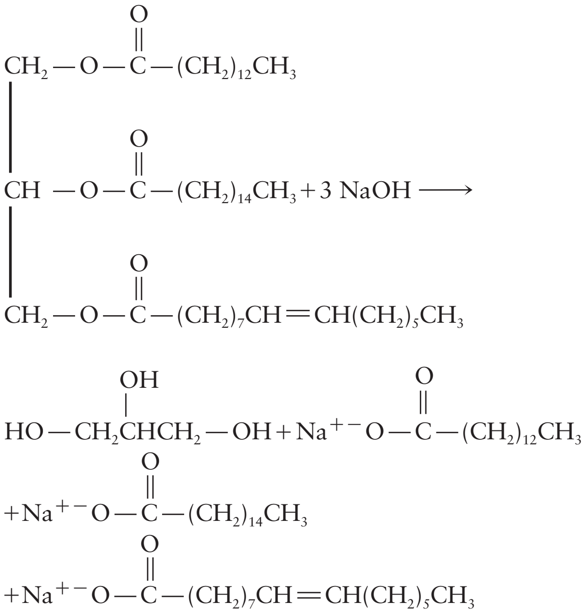
18.42 **a.**



$$\begin{array}{l} \mathrm{CH_2{-}O{-}\overset{O}{C}{-}(CH_2)_{12}CH_3} \\ | \\ \mathrm{CH\ {-}O{-}\overset{O}{C}{-}(CH_2)_{12}CH_3 + 3H_2O} \xrightarrow{H^+} \\ | \\ \mathrm{CH_2{-}O{-}\overset{O}{C}{-}(CH_2)_{12}CH_3} \end{array}$$

$$\mathrm{HO\ {-}CH_2\overset{OH}{C}HCH_2{-}OH + 3\ HO{-}\overset{O}{C}{-}(CH_2)_{12}CH_3}$$

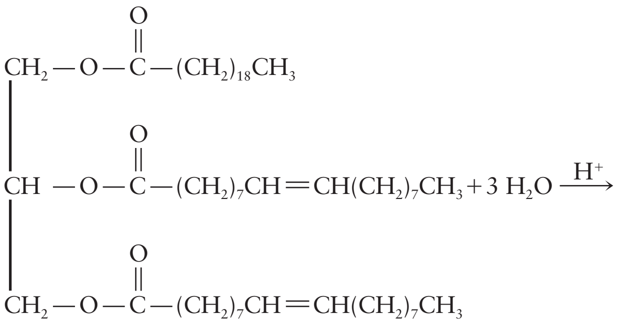
b. Butter-fat saponification would produce a mixture of salts (soaps) and glycerol.



$$\begin{array}{l} \mathrm{CH_2{-}O{-}\overset{O}{C}{-}(CH_2)_{12}CH_3} \\ | \\ \mathrm{CH\ {-}O{-}\overset{O}{C}{-}(CH_2)_{14}CH_3 + 3\ NaOH} \longrightarrow \\ | \\ \mathrm{CH_2{-}O{-}\overset{O}{C}{-}(CH_2)_7CH{=}CH(CH_2)_5CH_3} \end{array}$$

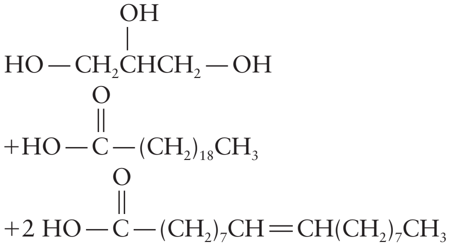
$$\begin{array}{l} \mathrm{HO{-}CH_2\overset{OH}{C}HCH_2{-}OH + Na^{+-}O{-}\overset{O}{C}{-}(CH_2)_{12}CH_3} \\ \mathrm{+Na^{+-}O{-}\overset{O}{C}{-}(CH_2)_{14}CH_3} \\ \mathrm{+Na^{+-}O{-}\overset{O}{C}{-}(CH_2)_7CH{=}CH(CH_2)_5CH_3} \end{array}$$

c. Several fatty acids could be shown as components of peanut oil.



$$\begin{array}{l} \mathrm{CH_2{-}O{-}\overset{O}{C}{-}(CH_2)_{18}CH_3} \\ | \\ \mathrm{CH\ {-}O{-}\overset{O}{C}{-}(CH_2)_7CH{=}CH(CH_2)_7CH_3 + 3\ H_2O} \xrightarrow{H^+} \\ | \\ \mathrm{CH_2{-}O{-}\overset{O}{C}{-}(CH_2)_7CH{=}CH(CH_2)_7CH_3} \end{array}$$

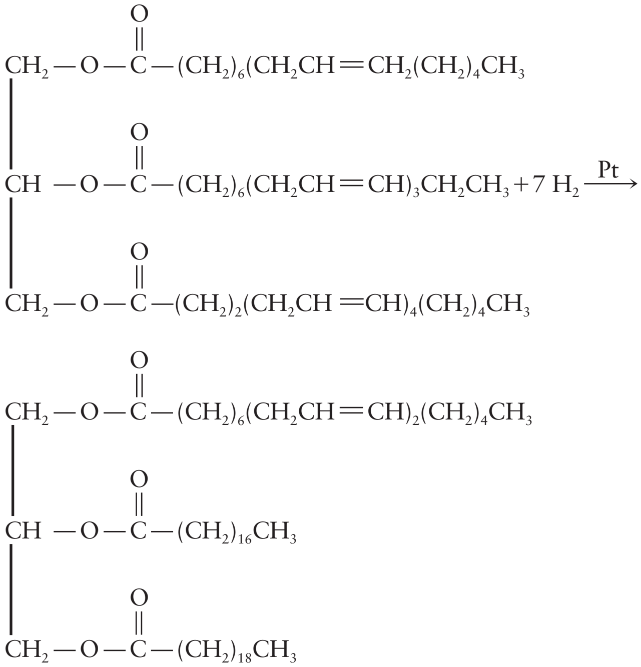
(Note: 3NaOH and saponification would also work)



$$\begin{array}{l} \mathrm{HO{-}CH_2\overset{OH}{C}HCH_2{-}OH} \\ \mathrm{+HO{-}\overset{O}{C}{-}(CH_2)_{18}CH_3} \\ \mathrm{+2\ HO{-}\overset{O}{C}{-}(CH_2)_7CH{=}CH(CH_2)_7CH_3} \end{array}$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

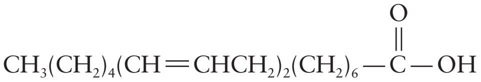
d. Several fatty acids could be shown as components of linseed oil. Partial hydrogenation of linseed oil will produce a higher melting semisolid.



$$\begin{array}{l} CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_6(CH_2CH{=}CH_2(CH_2)_4CH_3 \\ | \\ CH\;-O-\overset{\overset{O}{\|}}{C}-(CH_2)_6(CH_2CH{=}CH)_3CH_2CH_3 + 7\,H_2 \xrightarrow{Pt} \\ | \\ CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_2(CH_2CH{=}CH)_4(CH_2)_4CH_3 \\ \\ CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_6(CH_2CH{=}CH)_2(CH_2)_4CH_3 \\ | \\ CH\;-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{16}CH_3 \\ | \\ CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{18}CH_3 \end{array}$$

18.44 Fats are a triester between glycerol and fatty acids. Waxes are a monoester between a long-chain alcohol and a fatty acid.

18.46

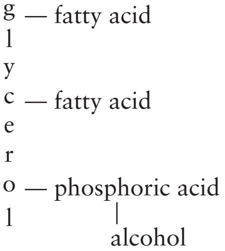


$$CH_3(CH_2)_4(CH{=}CHCH_2)_2(CH_2)_6-\overset{\overset{O}{\|}}{C}-OH$$

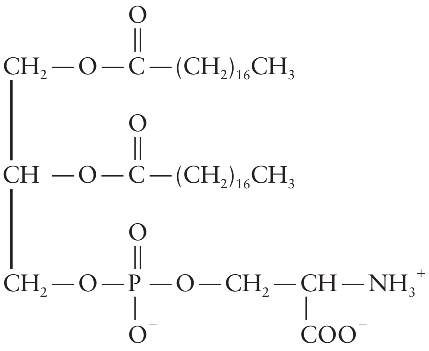
$HO-CH_2(CH_2)_{15}CH_3$

18.48 In nature, waxes often occur as protective coatings.

18.50



18.52



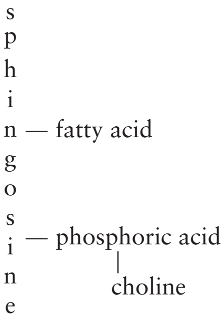
$$\begin{array}{l} CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{16}CH_3 \\ | \\ CH\;-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{16}CH_3 \\ | \\ CH_2-O-\underset{\underset{O^-}{|}}{\overset{\overset{O}{\|}}{P}}-O-CH_2-\underset{\underset{COO^-}{|}}{CH}-NH_3^+ \end{array}$$

This is a cephalin because it contains serine.

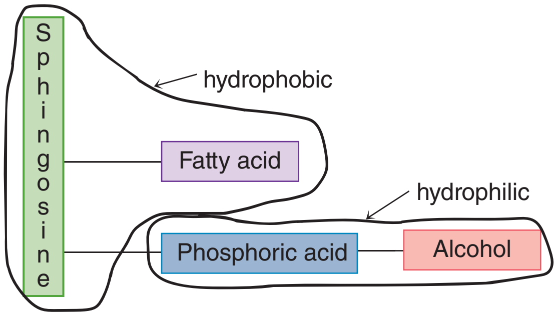
18.54 Lecithins serve as components in cell membranes and aid in lipid transport.

18.56 They differ in the identity of the amino alcohol portion. Lecithins contain choline, and cephalins contain ethanolamine or serine.

18.58



18.60



18.62 Tay-Sachs, Gaucher's, and Niemann-Pick

18.64 Cerebrosides, brain tissue

18.66 Phosphoglycerides, sphingomyelin, and cholesterol

18.68 The polarity of the phosphoglycerides contributes to their function of forming cell membranes by allowing a lipid bilayer to form with hydrophilic groups oriented to the outside and hydrophobic groups oriented to the inside.

18.70 It is suggested that some people restrict cholesterol intake in their diet because high levels of cholesterol in the blood are linked to atherosclerosis (hardening of the arteries).

18.72 Bile salts aid in the digestion of lipids by emulsifying lipids and breaking the large globules into many smaller droplets in order to increase the surface area available for hydrolysis reactions.

18.74 With a large hydrophobic region and an ionic region, sodium glycocholate functions like a soap, emulsifying cholesterol.

18.76 Cholesterol

18.78 The two groups are glucocorticoids and mineralocorticoids. Cortisol, a glucocorticoid, acts to increase the glucose and glycogen concentrations in the body. Aldosterone, a mineralocorticoid, regulates the retention of Na^+ and Cl^- during urine formation.

18.80 Testosterone; estradiol, estrone, and progesterone

18.82 Athletes use anabolic steroids to promote muscular development without excessive masculinization. The side effects of anabolic steroid use range from acne to deadly liver tumors. In males, anabolic steroid use can cause testicular atrophy, a decrease in sperm count, and temporary infertility.

18.84 Prostaglandins are characterized as cyclic compounds synthesized from the 20-carbon unsaturated fatty acid arachidonic acid. They contain a carboxylic acid group, various ring substituents, and side-chain double bonds.

18.86 Body processes regulated in part by prostaglandins are menstruation, conception, uterine contractions during childbirth, blood clotting, inflammation, and fever, to name only a few.

18.88 Induction of labor, treatment of asthma, treatment of peptic ulcers

18.90 The lipid is unsaturated (see Figure 12.5).

18.92 The phosphate and amino alcohol groups found in complex lipids are much more hydrophilic and capable of interacting with water than simple lipids.

18.94 Gasoline is soluble in nonpolar solvents, but it is not classified as a lipid because it does not come from a living organism.

18.96 Seeds are rich in oils because as a new plant begins to grow from the seed it needs energy from the oils (a low density, but calorie rich source) since the plant cannot photosynthesize until it has grown leaves.

18.98 Honey doesn't dissolve beeswax because honey is polar, consisting of sugars dissolved in water. Beeswax is nonpolar and will not be dissolved by a polar substance.

18.100 There are so many structurally different kinds of lipids because the lipid classification is based on solubility in a nonpolar solvent, not on structure.

18.102 When a doughnut is placed on a napkin, the napkin will often absorb a liquid and appear "moist." The nature of the liquid is most likely a nonpolar oil because the doughnut was fried in oil.

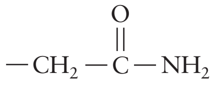
Chapter 19

19.2 The amine group ($-NH_2$) and the carboxylic acid group ($-COOH$), or the corresponding protonated $-NH_3^+$ group and unprotonated $-COO^-$ group.

19.4 a, d

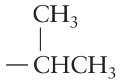
19.6 **a.** $-CH_2-SH$

b.



$$-CH_2-\overset{\overset{\displaystyle O}{\|}}{C}-NH_2$$

c.



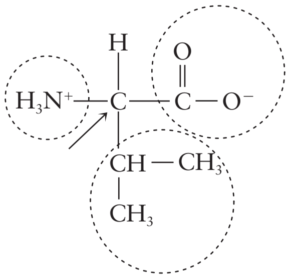
$$-\overset{\overset{\displaystyle CH_3}{|}}{C}HCH_3$$

d. $-CH_2-COO^-$

19.8

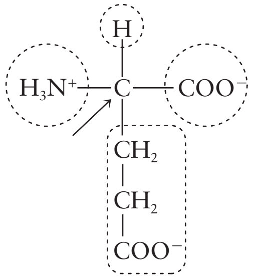
valine

a.



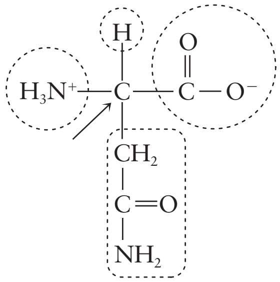
glutamate

b.



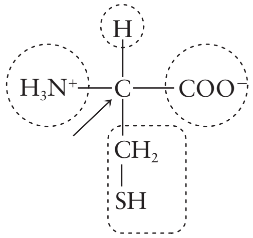
asparagine

c.

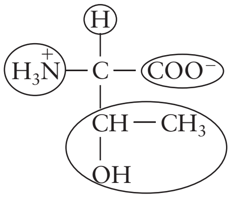


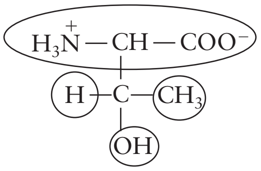
cysteine

d.

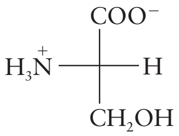


19.10

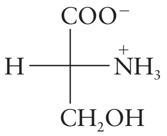




19.12 **a.**

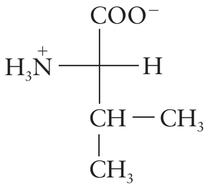


L-serine

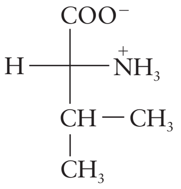


D-serine

b.



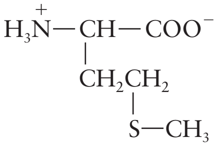
L-valine



D-valine

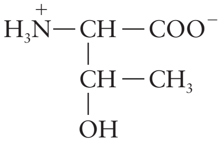
19.14 They are crystalline solids with relatively high melting points and high water solubilities.

19.16 **a.**



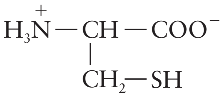
$H_3\overset{+}{N}-CH(CH_2CH_2-S-CH_3)-COO^-$

b.



$H_3\overset{+}{N}-CH(CH(OH)-CH_3)-COO^-$

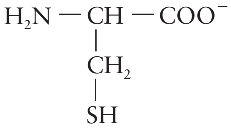
c.



$H_3\overset{+}{N}-CH(CH_2-SH)-COO^-$

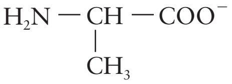
19.18

a.



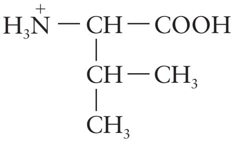
$H_2N-CH(CH_2-SH)-COO^-$

b.



$H_2N-CH(CH_3)-COO^-$

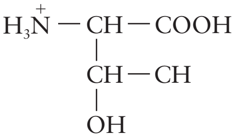
19.20 **a.**



$H_3\overset{+}{N}-CH(CH(CH_3)-CH_3)-COOH$

valine

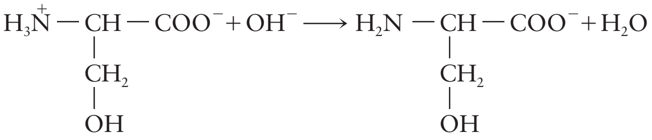
b.



$H_3\overset{+}{N}-CH(CH(OH)-CH)-COOH$

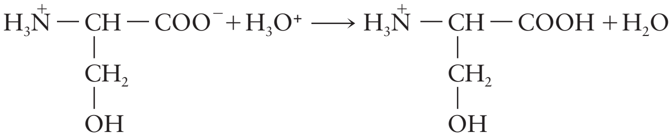
threonine

19.22 **a.**



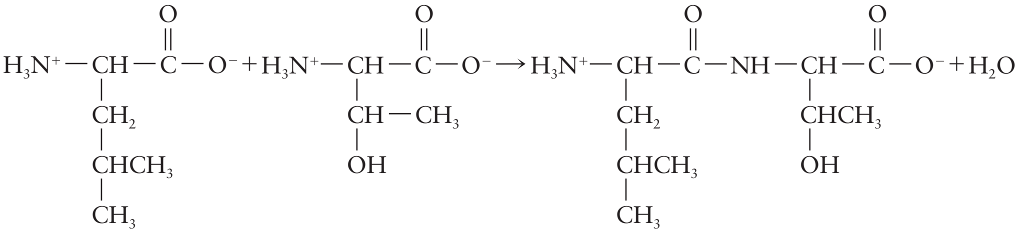
$H_3\overset{+}{N}-CH(CH_2-OH)-COO^- + OH^- \longrightarrow H_2N-CH(CH_2-OH)-COO^- + H_2O$

b.

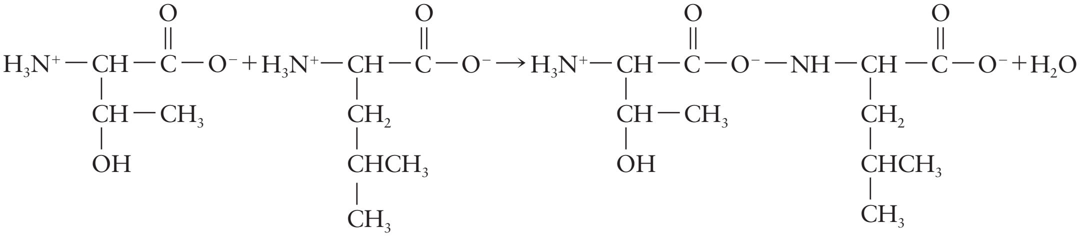


$H_3\overset{+}{N}-CH(CH_2-OH)-COO^- + H_3O^+ \longrightarrow H_3\overset{+}{N}-CH(CH_2-OH)-COOH + H_2O$

19.24

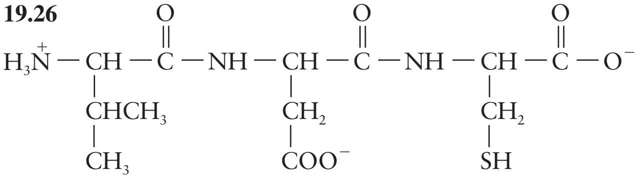


$H_3N^+-CH(CH_2-CHCH_3-CH_3)-\overset{O}{\overset{\|}{C}}-O^- + H_3N^+-CH(CH(OH)-CH_3)-\overset{O}{\overset{\|}{C}}-O^- \rightarrow H_3N^+-CH(CH_2-CHCH_3-CH_3)-\overset{O}{\overset{\|}{C}}-NH-CH(CHCH_3-OH)-\overset{O}{\overset{\|}{C}}-O^- + H_2O$



$H_3N^+-CH(CH(OH)-CH_3)-\overset{O}{\overset{\|}{C}}-O^- + H_3N^+-CH(CH_2-CHCH_3-CH_3)-\overset{O}{\overset{\|}{C}}-O^- \rightarrow H_3N^+-CH(CH(OH)-CH_3)-\overset{O}{\overset{\|}{C}}-O^- -NH-CH(CH_2-CHCH_3-CH_3)-\overset{O}{\overset{\|}{C}}-O^- + H_2O$

19.26

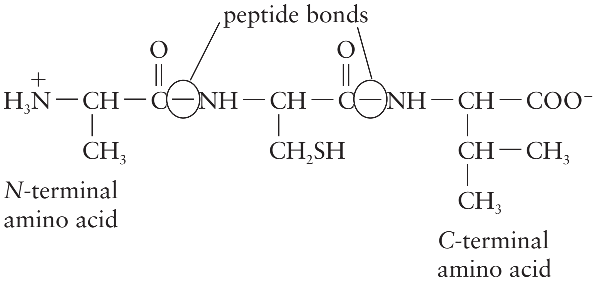


$H_3\overset{+}{N}-CH(CHCH_3-CH_3)-\overset{O}{\overset{\|}{C}}-NH-CH(CH_2-COO^-)-\overset{O}{\overset{\|}{C}}-NH-CH(CH_2-SH)-\overset{O}{\overset{\|}{C}}-O^-$

Val-Asp-Cys

19.28 alanine–cysteine–valine

19.30



$H_3\overset{+}{N}-CH(CH_3)-\overset{O}{\overset{\|}{C}}-NH-CH(CH_2SH)-\overset{O}{\overset{\|}{C}}-NH-CH(CH-CH_3(CH_3))-COO^-$

19.32 Ala-Phe-Arg, Phe-Arg-Ala, Arg-Ala-Phe

Ala-Arg-Phe, Phe-Ala-Arg, Arg-Phe-Ala

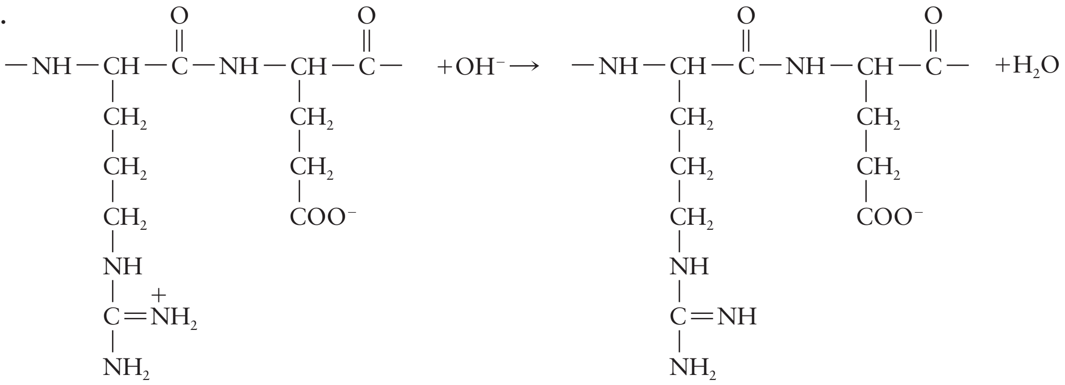
19.34 Six

19.36 Each peptide contains a disulfide bridge in which two cysteines have been linked.

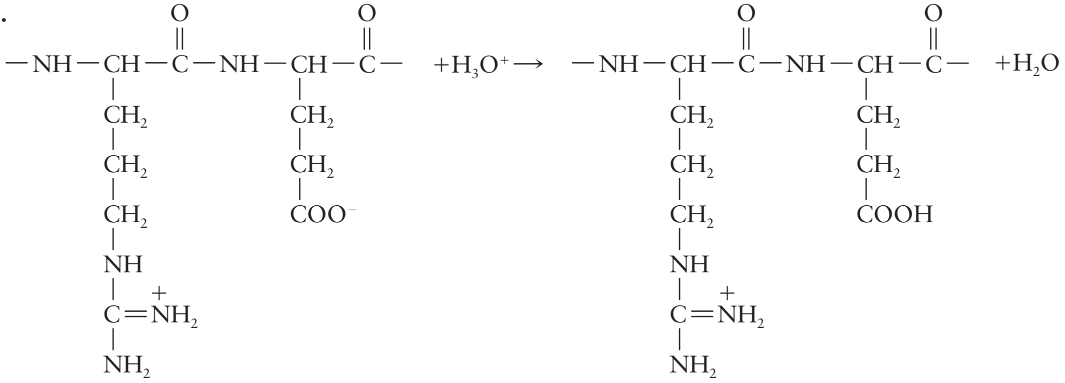
19.38 Both peptides contain nine amino acid units. Counting from the *N*-terminal end, they differ in the amino acid residues 3 and 8.

19.40 Normally, proteins do not pass through membranes, and the appearance of an abnormal protein in blood or urine indicates cellular damage, which has released those substances.

19.42 **a.**



b.



19.44 Wool is a protein used as a textile fiber. It is a structure protein.

19.46

a.	insulin	regulation
b.	collagen	structure
c.	hemoglobin	transport
d.	cytochrome c	catalysis

19.48 **a.** Fibrous; collagen is a structural protein.

b. Globular; lactate dehydrogenase is an enzyme and needs to be water soluble.

19.50 Simple proteins contain only amino acid residues, whereas conjugated proteins contain additional components.

19.52 **a.** Gamma globulin (mucin)

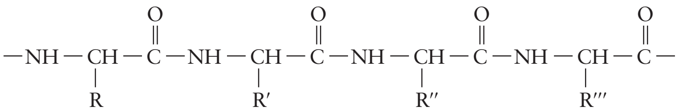
b. Hemoglobin (myoglobin, cytochromes)

c. Viruses

d. Alcohol dehydrogenase

19.54 Even though two polypeptides have the same amino acid composition, the sequence of amino acids may be different. A different order of amino acids would give rise to a different three-dimensional structure and thus different functions.

19.56



$$-NH-\underset{R}{\underset{|}{CH}}-\overset{O}{\overset{\|}{C}}-NH-\underset{R'}{\underset{|}{CH}}-\overset{O}{\overset{\|}{C}}-NH-\underset{R''}{\underset{|}{CH}}-\overset{O}{\overset{\|}{C}}-NH-\underset{R'''}{\underset{|}{CH}}-\overset{O}{\overset{\|}{C}}-$$

19.58 The formation of secondary structures (α-helix and the β-pleated sheet) arises from hydrogen bonding between amide groups and is independent from the primary structure.

19.60 Supracoiling in proteins occurs when two or more helices interact to form a cable.

19.62 The formation of salt bridges can only occur if the side chain is charged. The amino acids with side-chain groups that can form salt bridges are histidine, lysine, arginine, aspartate, and glutamate.

19.64 **a.** Hydrophobic interactions

b. Salt bridge

c. Hydrogen bonding

d. Disulfide bridge

19.66 c, d

19.68 The nonpolar R groups in phenylalanine, alanine, and methionine will point inward; the polar R groups in glutamate and lysine will point toward the water.

19.70 Quaternary protein structure is the arrangement of subunits that form a larger protein.

19.72 The quaternary structure of hemoglobin is four subunits (two alpha chains containing 141 amino acid residues each and two beta chains containing 146 residues each) that each contain a heme group (a planar ring structure centered around an iron atom) located in crevices near the exterior of the molecule. The molecule is nearly spherical with the four subunits held together rather tightly by hydrophobic forces.

19.74 Denaturation is the process by which a protein loses its characteristic native structure and function.

19.76 Ser – Asn – Leu – Lys – Phe – Trp

19.78 All structural levels.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

19.80 If protein medications were taken by month, the proteins would be denatured and hydrolyzed by the acidic contents of the stomach.

19.82 The primary structure of the protein is the same.

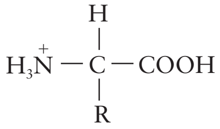
19.84 Cooking egg white is an irreversible denaturation. Whipping air into them is a reversible denaturation.

19.86 The heavy metal ions denature the protein in the egg white by interacting with the —SH groups and the carboxylate ($—COO^-$) groups. Vomiting should then be induced to remove the denatured proteins so they are not digested, releasing the metal ions.

19.88 Valine, methionine, and threonine

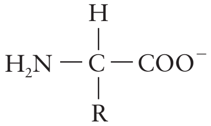
19.90

Conjugate acid:



$H_3\overset{+}{N}—\underset{R}{\overset{H}{C}}—COOH$

Conjugate base:



$H_2N—\underset{R}{\overset{H}{C}}—COO^-$

Chapter 20

20.2 Enzymes are highly specific in the reactions they catalyze, and their activity as catalysts can be regulated.

20.4 Each one is specific for a single type of reaction and often is specific for a single substrate.

20.6 Enzymes that are specific for a single reactant exhibit absolute specificity.

20.8 Enzyme Commission (EC) system

20.10 a, d

20.12 **a.** Hydrolase
- **b.** Transferase
- **c.** Lyase
- **d.** Ligase

20.14 **a.** Sucrose
- **b.** Amylose
- **c.** Lactose
- **d.** Maltose
- **e.** Arginine

20.16

	Enzyme	Reaction Catalyzed
a.	Decarboxylase	removal of carboxyl groups from compounds
b.	Phosphatase	hydrolysis of phosphate ester linkages
c.	Peptidase	hydrolysis of peptide linkages
d.	Esterase	formation of ester linkages

20.18 **a.** Catalyzes the dehydrogenation (oxidation) of succinate
- **b.** Catalyzes the reduction of L-amino acids
- **c.** Catalyzes the oxidation of cytochrome
- **d.** Catalyzes the isomerization of glucose-6-phosphate

20.20 **a.** Nitrite oxidase
- **b.** Fructose isomerase
- **c.** Lactate dehydrogenase
- **d.** Lactose hydrolase

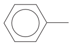
20.22 **a.** Conjugated
- **b.** Conjugated
- **c.** Simple
- **d.** Conjugated

20.24 **a.** An inorganic ion cofactor
- **b.** A nonspecific component cofactor
- **c.** An organic material coenzyme
- **d.** Nicotinic acid coenzyme

20.26 An enzyme is a catalytically active structure made up of a protein portion called an apoenzyme and a nonprotein portion called a cofactor.

20.28 Mg^{2+}, Zn^{2+}, Fe^{2+}, Ca^{2+}

20.30 E = enzymes, S = substrate, ES = enzyme–substrate complex, and P = product of reaction. Thus $E + S \rightleftarrows ES \rightarrow E + P$ represents the reaction of an enzyme with a substrate molecule to form an enzyme–substrate complex, which then gives the reaction product and regenerates the enzyme.

20.32 **a.** $CH_3CH_2—OH$ and $HO—$
- **b.** $CH_3CH_2—COO^-$ and Fe^{2+}
- **c.** $CH_3CH_2CH_2CH_2CH_3$ and 

20.34 Covalent bonds are strong bonds, too strong to permit the eventual release of the substrate.

20.36 The lock-and-key theory states that the active site of the enzyme is rigid (like a lock) and the substrate acts (like a key) by entering the active site. The induced fit model states that the active site of the enzyme accommodates the substrate and is not rigid but has a shape that becomes complementary to that of the substrate only after the substrate is bound.

20.38 Enzyme activity can be described as the turnover number (the number of molecules of substrate acted on by one molecule of enzyme per minute) or in terms of enzyme international units (IU) (enzyme activity as the amount of enzyme that will convert a specified amount of substrate to a product within a certain time).

20.40 The turnover number is the number of molecules of substrate acted on by one molecule of enzyme per minute.

20.42 60 times 1.5×10^6 or 9.0×10^7 molecules

20.44 1.6×10^{10} Iμ

20.46 **a.** The enzyme activity (rate of reaction) increases with increased substrate concentration until all the enzyme is utilized, at which point no further increase in rate occurs.
- **b.** The activity (rate) increases with an increase in enzyme concentration.
- **c.** There is an optimum pH for the reaction, so at a pH above or below the optimum value, the rate will decrease.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

- **d.** The activity (rate) increases up to a maximum as the temperature increases, and then decreases with further temperature increase.

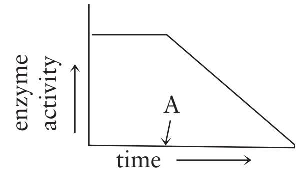
20.48 Prepare a series of reactions with constant enzyme amount and increasing substrate amounts. Plot reaction rate versus substrate concentration. A constant rate at higher substrate concentrations is V_{max}.

20.50 With more enzyme present, the V_{max} will be higher than it should be.

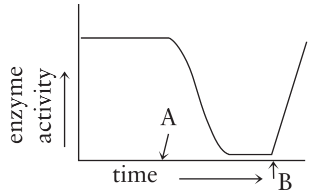
20.52 Enzyme structures are unique, so enzyme properties are also unique.

20.54 Irreversible enzyme inhibition involves the formation of a covalent bond between an irreversible inhibitor and the enzyme which renders the enzyme inactive. This is not reversible because the bond between enzyme and inhibitor is extremely strong. Reversible enzyme inhibition involves the reversible binding, which may or may not be covalent, of a reversible inhibitor to an enzyme. An equilibrium is established; therefore, the inhibitor can be removed from the enzyme by shifting the equilibrium.

20.56



20.58



20.60
- **a.** Reversible-competitive
- **b.** Reversible-noncompetitive
- **c.** Irreversible, reversible noncompetitive
- **d.** Irreversible, reversible noncompetitive

20.62
- **a.** Cyanide reacts with the iron of the cytochrome oxidase enzyme and forms a very stable complex, which prevents the enzyme from performing its normal function.
- **b.** Heavy metal ions react with the –SH groups found on many enzymes to cause nonspecific protein denaturation.

20.64 The regulation of enzyme activity is necessary because of the changing conditions around the living organism and changing cellular needs within the living organism.

20.66 A zymogen is the inactive precursors of an enzyme. Some enzymes in their active form would degrade the internal structures of the cells and, ultimately, the cells themselves; therefore, these enzymes are synthesized and stored as zymogens. When the active enzyme is needed, the stored zymogen is released from storage and activated at the location of the reaction. Examples of enzymes with a zymogen are digestive enzymes (pepsin, trypsin, and chymotrypsin) and several of the enzymes involved in blood clotting.

20.68 Activation usually involves the cleavage of one or more peptide bonds of the zymogen.

20.70 Modulators may increase activity (activators) or decrease the activity (inhibitors).

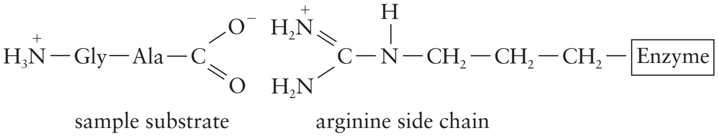
20.72 In feedback enzyme inhibition, an end product of a sequence of enzyme-catalyzed reactions inhibits an earlier step in the process. This is advantageous for the cell because it allows the concentration of cellular products to be maintained within very narrow limits.

20.74 Enzyme assays of blood serum are useful in a clinical diagnosis because certain enzymes are normally found almost exclusively inside tissue cells and are released into the blood and other biological fluids only when these cells are damaged or destroyed. The presence of these enzymes in blood allows for the diagnosis of a pathological condition.

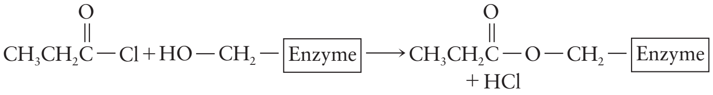
20.76
- **a.** Useful in diagnosing prostate cancer
- **b.** Useful in diagnosing acute pancreatitis
- **c.** Useful in diagnosing heart attack or hepatitis

20.78 An LDH assay is a good initial diagnostic test because the isoenzyme forms of LDH are so widespread in the human system. Thus, the locations of diseases can be pinpointed.

20.80 An ionic bond is formed:



20.82 A covalent ester linkage is formed between the acid chloride and the —OH of the serine:



$$CH_3CH_2\overset{\overset{O}{\|}}{C}-Cl+HO-CH_2-\boxed{Enzyme}\longrightarrow CH_3CH_2\overset{\overset{O}{\|}}{C}-O-CH_2-\boxed{Enzyme}+HCl$$

20.84 There will be no shift in the equilibrium. Enzymes are catalysts and cannot change the position of equilibrium, only the speed of which an equilibrium is reached.

20.98 c

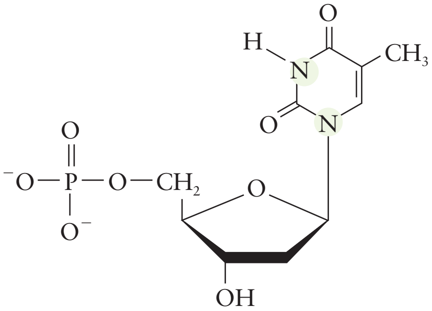
Chapter 21

21.2 Deoxyribose in DNA, ribose in RNA

21.4
- **a.** Purine
- **b.** Pyrimidine
- **c.** Pyrimidine
- **d.** Pyrimidine
- **e.** Purine

21.6
- **a.** Deoxyribose
- **b.** Adenine, guanine, cytosine, uracil
- **c.** Phosphate

21.8



Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

21.10 **a.** False

b. False

c. True

d. False

21.12 Two DNA molecules that contain the same number of nucleotides may differ in the order as well as relative numbers of the bases.

21.14 The data obtained from the chemical analysis of DNA that supported the idea of complementary base pairing in DNA proposed by Watson and Crick was that in all DNA the percentages of adenine and thymine were always equal to each other as were the percentages of guanine and cytosine.

21.16 The role of hydrogen bonding in the secondary structure of DNA is to stabilize the DNA structure by holding the two strands together.

21.18 **a.** GCATGC 16 hydrogen bonds

b. TATGGC 15 hydrogen bonds

21.20 Strand A and its complementary strand exhibit 16 hydrogen bonds, while strand B and its complementary strand have just 15 hydrogen bonds.

21.22 **a.** 14%

b. 36%

c. 14%

21.24 $5'$ GATTCA $3'$ original strand

$3'$ CTAAGT $5'$ complementary strand

$5'$ TGAATC $3'$ complementary strand read $5' \rightarrow 3'$

21.26 21% T, 29% G, 36% C, and 14% A

21.28 *Semiconservative replication* means a replication process in which DNA molecules contain one strand from the parent and a new strand that is complementary to the strand from the parent.

21.30 The function of the enzyme helicase in the replication of DNA is to catalyze the separation and unwinding of the nucleic acid strands at a specific point along the DNA helix.

21.32 The enzymes involved in DNA replication are helicase, DNA polymerase, and DNA ligase.

21.34 The synthesis of a DNA daughter strand growing toward a replication fork grows continuously. A daughter strand growing away from a replication fork has Okazaki fragments separated by nicks.

21.36 **a.** GTACGT
CATGCA

b. $\left.\begin{array}{l}\text{Old strand } 5' \text{ GTACGT } 3' \\ \text{New strand } 3' \text{ CATGCA } 5'\end{array}\right\}$ daughter DNA molecule

$\left.\begin{array}{l}\text{New strand } 5' \text{ GTACGT } 3' \\ \text{Old strand } 3' \text{ CATGCA } 5'\end{array}\right\}$ daughter DNA molecule

21.38 **a.** CCAGTT

b. CCAGTT

c. AACTGG

21.40 Response c is correct. The repeating nucleotide units of a DNA strand are linked together by $3'$ to $5'$ phosphodiester linkages.

21.42 DNA has two intertwined complementary strands joined by hydrogen bonds in a double helix. RNA has a single strand that has some regions of double-helical structure where complementary bases are joined by hydrogen bonds and some regions without hydrogen bonding that are loops.

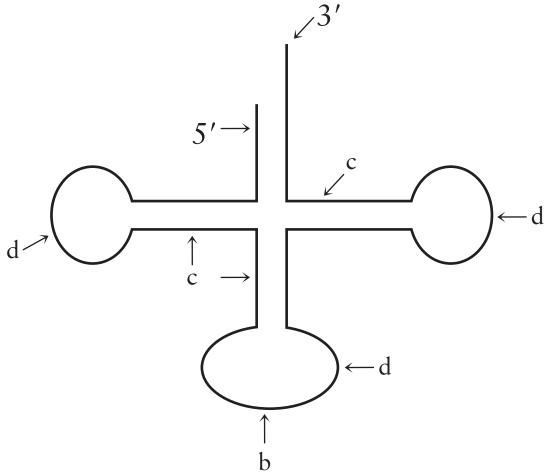
21.44 **a.** rRNA

b. mRNA

c. tRNA

21.46 The ratio of guanine to cytosine does not have to be 1:1 in RNA because RNA is single-stranded (unlike double-stranded DNA) and does not contain a matched set of complementary bases.

21.48



21.50 Transcription is the transferring of genetic DNA information to messenger RNA. Translation is the expression of messenger RNA information in the form of an amino acid sequence in a protein.

21.52 $5'$ CAAUAUGGC $3'$

21.54 RNA strand $5'$ UUGCGAAUC $3'$
DNA strand $3'$ AACGCTTAG $5'$

Written $5' \rightarrow 3'$ DNA strand is GATTCGCAA

21.56 CGUA

21.58 In prokaryotic cells, transcription to mRNA is followed almost immediately by translation into a protein because there is no nuclear membrane in prokaryotic cells to separate the DNA from the cytoplasm. In eukaryotic cells, transcription to hnRNA occurs in the nucleus. The hnRNA undergoes a series of enzyme-catalyzed reactions that cut and splice hnRNA into mRNA. The mRNA translation into a protein occurs in the cytoplasm. The overall process is slower.

21.60 A codon is a sequence of three nucleotide bases that represents a "code word" on the mRNA molecules. Each codon provides genetic code information for a specific amino acid.

21.62 **a.** $5'$ UAC $3'$ valine

b. $5'$ GGG $3'$ proline

c. $5'$ GUG $3'$ histidine

d. $5'$ UGG $3'$ proline

21.64 Glutamic acid-aspartic acid-leucine-glycine-glycine

21.66 All codons are three letters.

21.68 **a.** False; should be three bases.

b. True

c. False; 61 of 64 codons represent amino acids.

d. False; each living species is thought to use the same genetic code.

e. True

f. False; stop signals for protein synthesis are represented by three codons: UAA, UAG, and UGA.

21.70 A complex of mRNA and several ribosomes; also called polyribosome.

21.72 Initiation, elongation, termination

21.74 The A site (aminoacyl site) is where an incoming tRNA carrying the next amino acid will bond. The P site (peptidyl site) is where the tRNA carrying the peptide chain is located.

21.76 A change in the DNA of a cell wherein a wrong base sequence is produced on the DNA.

21.78 The protein synthesized would contain a proline rather than an alanine residue at that site in the protein.

21.80 **a.** Serine–glycine–isoleucine–tryptophan

b. Threonine–glycine–isoleucine–tryptophan

c. Serine–glycine–isoleucine–tryptophan

21.82 Recombinant DNA is DNA of one organism that contains segments of DNA from another organism.

21.84 Human insulin will become widely available for treating diabetes. Human growth hormone will be used for treating pituitary disorders. Recombivax Hb, a vaccine for hepatitis B, will be marketed.

21.86 Hydrolysis of the phosphodiester linkage would break the nucleic acid backbone and allow the removal of intron segments. Esterification (ester formation) of the $5'\text{—}PO_4^{2-}$ group of one exon segment to the $3'\text{—}OH$ group of another exon segment would be used to join exons.

21.88 **a.** Glucose and fructose

b. Enzyme induction

c. Somehow the presence of sucrose activates the bacterial cell's DNA to produce more copies of mRNA that codes for enzyme Q.

Chapter 22

22.2 Macronutrients are needed in large quantities per day (1 gram or more). Micronutrients are needed in small quantities (milligrams or less).

22.4 0.5 tsp

22.6 11 potatoes

22.8 15 potatoes

22.10

Carbohydrates	Energy source Provide materials for cell and tissue synthesis
Proteins	Provide amino acids for cell repair and maintenance Provide ingredients for the synthesis of enzymes and hormones
Lipids	Energy source; solvent for fat-soluble vitamins Source of essential fatty acids

22.12 **a.** Carbohydrates

b. Proteins

c. Lipids

d. Lipids

22.14 **a.** Protein

b. Carbohydrate

c. Lipid

22.16 **a.** Carbohydrates, lipids, proteins

b. Carbohydrates, lipids, proteins

c. Carbohydrates, proteins

d. Carbohydrates, lipids, proteins

22.18 Linoleic acid is called an essential fatty acid for humans because humans cannot synthesize this compound. It must be obtained from the diet.

22.20 $80\ \cancel{g}\text{ fat}\left(\frac{9\text{ cal}}{1\ \cancel{g}}\right) = 720\text{ cal from fat}$

$20\ \cancel{g}\text{ fat}\left(\frac{9\text{ cal}}{1\ \cancel{g}}\right) = 180\text{ cal from saturated fat}$

$280\ \cancel{g}\text{ carbohydrate}\left(\frac{4\text{ cal}}{1\ \cancel{g}}\right) = 1.12 \times 10^3\text{ cal from carbohydrate}$

Note: The significant figures from the calorie per gram conversion were ignored in these calculations.

22.22 **a.** Fat-soluble

b. Water-soluble

c. Water-soluble

d. Water-soluble

22.24 Fat-soluble

22.26 Water-soluble vitamins can be excreted in water-based fluids much more readily than fat-soluble vitamins. Thus, large doses of fat-soluble vitamins accumulate in the body.

22.28 **a.** Vitamin C

b. Vitamin B_1

c. Vitamin B_{12}

d. Niacin

22.30

Ca:	component of bones and teeth; regulation of muscle activity
P:	component of bones and teeth, nucleic acids, phospholipids, and enzymes
K:	charge balance in cells; regulates heartbeat
S:	component of the amino acid cysteine; charge balance in cells (as SO_4^{2-})
Na:	charge balance in cells
Cl:	charge balance in cells
Mg:	component of enzymes; regulation of muscle activity

22.32 Drinks containing NaCl and KCl would serve to replace those compounds lost in perspiration, preventing muscle weakness and cramps.

22.34 The ionic form of many elements, including iodine, is the form required by the body.

22.36 Hydrogen

22.38 $6CO_2 + 6H_2O + \text{energy} \rightarrow C_6H_{12}O_6 + 6O_2$

22.40 The Earth's supply of carbon compounds may be recycled by the processes of photosynthesis and respiration because during photosynthesis CO_2 is used to produce glucose, while during respiration glucose is converted to CO_2.

22.42 The carbon atoms of the world are recycled many times through plants and animals. Plants incorporate gaseous CO_2 into carbohydrates. Animals eat carbohydrates, which when burned by the body, regenerate CO_2.

22.44 A metabolic pathway is a sequence of reactions used to produce one ultimate product or accomplish one overall process. The product(s) of one reaction is(are) used up in the next reaction in the sequence so that all the reactions are essential to the overall process.

22.46 Catabolism is an energy-producing process and anabolism an energy-consuming process.

22.48 Cellular respiration is catabolic because it involves a breakdown of biomolecules and generates energy.

22.50 **a.** Stage III

b. Stage I

c. Stage III

d. Stage II

22.52 Stage III of energy production is referred to as the common catabolic pathway because all macronutrients have been converted to acetyl CoA and go through the citric acid cycle, electron transport chain, and oxidative phosphorylation. This stage is, therefore, common to all macronutrients.

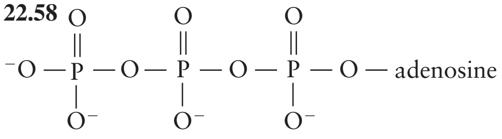
22.54 The digestion of protein to amino acids that are then used to build muscle in the body would not be considered a catabolic pathway. The digestion is a catabolic process; however, building muscle tissue is an anabolic process. These two processes together cannot be a catabolic pathway, since one of the steps is an anabolic process.

22.56 ATP represents adenosine triphosphate.

ADP represents adenosine diphosphate.

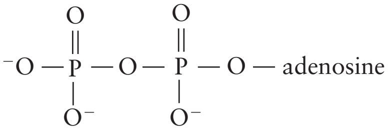
AMP represents adenosine monophosphate.

22.58



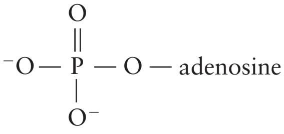
$$^{-}O-\overset{O}{\underset{O^-}{P}}-O-\overset{O}{\underset{O^-}{P}}-O-\overset{O}{\underset{O^-}{P}}-O-\text{adenosine}$$

ATP



$$^{-}O-\overset{O}{\underset{O^-}{P}}-O-\overset{O}{\underset{O^-}{P}}-O-\text{adenosine}$$

ADP



$$^{-}O-\overset{O}{\underset{O^-}{P}}-O-\text{adenosine}$$

AMP

22.60 $ATP + H_2O \rightarrow ADP + Pi + H^+$

$ATP + H_2O \rightarrow AMP + PPi + 2H^+$

22.62 **a.** Phosphoenolpyruvate

b. Phosphocreatine

c. 1,3-bisphosphoglycerate

d. AMP

22.66 Anabolic processes require energy and should have a $+\Delta G°'$

22.68 ATP is a carrier or donor of free energy because it is hydrolyzed within one minute of its formation.

22.70 The importance and function of the ATP–ADP cycle is to supply energy for motion, biosynthesis, and other forms of cellular work.

22.72 **a.** Riboflavin FAD

b. Pantothenic acid coenzyme A

c. Nicotinamide NAD^+

22.74 **a.** Flavin adenine dinucleotide FAD (oxidized) and $FADH_2$ (reduced)

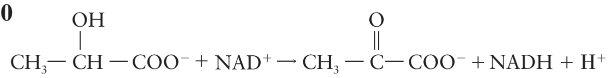
b. Nicotinamide adenine dinucleotide NAD^+ (oxidized) and NADH (reduced)

22.76 The conversion of NAD^+ to NADH is a synthetic step requiring an input of energy, so it will have a $+\Delta G°'$.

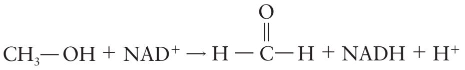
22.78 CH_3CH_2-OH is oxidized from an alcohol to an aldehyde.

NAD^+ is reduced to NADH.

22.80

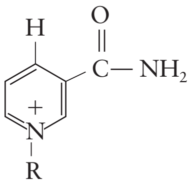
a. 

$$CH_3-\overset{OH}{CH}-COO^- + NAD^+ \rightarrow CH_3-\overset{O}{\overset{\|}{C}}-COO^- + NADH + H^+$$

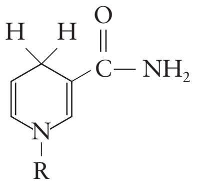
b. 

$$CH_3-OH + NAD^+ \rightarrow H-\overset{O}{\overset{\|}{C}}-H + NADH + H^+$$

22.82



NAD^+



NADH

22.84 $CH_4 + O_2 + 2\,NAD^+ \rightarrow CO_2 + 2\,NADH + 2\,H^+$

A total of four electrons are transferred to the 2NADH molecules.

22.86 Protein synthesis, translation

Chapter 23

23.2 **a.** Glucose

b. Glucose and galactose

c. Glucose and fructose

d. Glucose

23.4 Like glucose, fructose and galactose are absorbed into the bloodstream and transported to the liver. There they are converted into glucose or other glucose pathways.

23.6 Blood sugar level is the concentration of glucose in the blood. The normal fasting level is the blood glucose concentration after a fast of 8–12 hours.

23.8 **a.** A blood sugar level below the normal range.

b. A blood sugar level above the normal fasting level.

c. A blood sugar level at which glucose is not reabsorbed by the kidneys.

d. An elevated blood sugar level resulting in the excretion of glucose in the urine.

23.10 Insulin could be used to lower higher levels of blood glucose (hyperglycemia).

23.12 The liver responds to the increase in blood glucose that follows a meal by removing glucose from the bloodstream and converting it to glycogen or triglycerides for storage. When blood glucose levels are low, the liver responds by converting stored glycogen to glucose and by synthesizing new glucose from noncarbohydrate substances.

23.14 The main purpose of glycolysis is to provide energy for the body from carbohydrates.

23.16 Glycolysis occurs in the cellular cytoplasm.

23.18 The oxidizing agent in glycolysis is NAD$^+$.

23.20 No steps in glycolysis require NADH. Two steps in glycolysis produce NADH, producing a net 2 NADH from one glucose.

23.22 Allosteric regulation is a process involving an enzyme whose activity is affected by the binding of modulators.

23.24 **a.** Fructose-6-phosphate

b. Fructose-1,6-bisphophate

c. Pyruvate kinase

d. ATP

23.26 Glucose-6-phosphate is a feedback inhibitor of the enzyme hexokinase and causes a decrease in the enzymatic turnover rate (activity) of that enzyme.

23.28 Aerobic denotes the presence of oxygen, whereas anaerobic means without oxygen.

23.30 Glyceraldehyde-3-phosphate → 1,3-bisphosphoglycerate

23.32 Lactate formation allows glycolysis to continue under anaerobic conditions by reducing pyruvate to lactate as a means of regenerating NAD$^+$.

23.34 **a.** Glucose $+ \text{2ADP} + 2\text{P}_i \rightarrow$ 2 lactate + 2 ATP

b. Glucose $+ 2\text{NAD}^+ + \text{2ADP} + 2\text{P}_i \rightarrow \text{2ATP} +$ 2 pyruvate $+ \text{2NADH} + 2\text{H}^+$

c. Glucose $+ \text{2ADP} + 2\text{P}_i \rightarrow$ 2 ethanol $+ 2\text{CO}_2 + \text{2ATP}$

23.36 It is released as CO_2. Ethanol formation allows the yeast to regenerate NAD$^+$ in the absence of oxygen and still generate sufficient ATP to sustain life.

23.38 The citric acid cycle is the principal process for generating NADH and FADH_2, which are necessary for ATP synthesis. The citric acid cycle is also important as a source of intermediates in the biosynthesis of amino acids.

23.40 **a.** acetyl CoA

b. CO_2

c. NADH and FADH_2

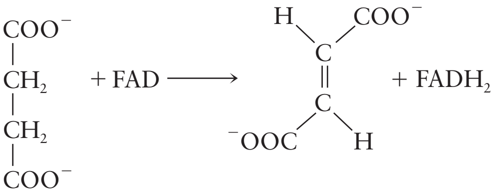
23.42 **a.** Three

b. One

c. One

d. Two

23.44



23.46 Isocitrate + NAD$^+$ → α-ketoglutarate + NADH + CO_2

α-ketoglutarate + NAD$^+$ + CoA-SH → succinyl CoA + NADH + CO_2

23.48 **a.** Step 1, citrate synthetase

Step 3, isocitrate dehydrogenase

Step 4, α-ketoglutarate dehydrogenase

b. When supplies of NADH and ATP are abundant, the cell has sufficient energy for its needs, so the operation of the citric acid cycle is inhibited.

c. As the cell uses ATP and makes ADP, the enzymes controlling the cycle are activated to make more ATP.

23.50 **a.** Within the cytoplasm of the cell

b. Within mitochondria

c. Within mitochondria

23.52 The participants of the electron transport chain in the order they accept electrons are: FMN, Fe-S, CoQ, cyt *b*, Fe-S, cyt c_1, cyt *c*, cyt *a*, cyt a_3, oxygen.

23.54 Cytochromes pass electrons along the electron transport chain to oxygen, which combines with H$^+$ ions to form water.

23.56 Iron deficiency might impact the electron transport chain, thus reducing the utilization of oxygen and the production of energy.

23.58 When NADH passes electrons to molecular oxygen, 2.5 ATP molecules are synthesized. Again, note that no process can in reality produce ½ a molecule of any substance. This statement simply gives the ratio of NADH to ATP and allows us to keep an accounting of ATP per unit of substrate.

23.60 Oxidation of NADH in the electron transport chain results in 34% energy conservation because the oxidation of NADH liberates 52.6 kcal/mol, while the oxidation and phosphorylation reactions conserve 18 kcal of the 52.6 kcal that are liberated.

$$\frac{18\text{ kcal}}{52.6\text{ kcal}} \times 100 = 34\%$$

23.62 10.0 ATP

23.64 The steps in the electron transport chain where ATP is synthesized are:

NADH → flavin mononucleotide

cytochrome *b* → Fe–S protein

cytochrome a, $a_3 \rightarrow \text{O}_2$

23.66 The function of the protein F1-ATPase is to form a channel for protons to flow back through the inner mitochondrial membrane to the space between the inner and outer membranes. This replaces the hydrogen ions, so that they are available to be "pumped" back again for the production of more ATP.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

23.68 Normally, each unit of NADH oxidized in the electron transport chain produces 2.5 molecules of ATP. Muscle cells, however, employ a transport mechanism that passes electrons from the cytoplasmic NADH through the membrane to FAD molecules inside the mitochondria, forming FADH2, which only gives 1.5 molecules of ATP using the electron transport chain per FAD unit, using the electron transport chain.

23.70 **a.** 5 ATP

b. 5 ATP (3 ATP in muscle and brain cells)

c. 2 ATP

23.72 The complete oxidation of glucose to CO_2 and H_2O produces 32 ATP (30 ATP in muscle and brain cells). Glucose to lactate produces 2 ATP.

23.74 Fructose and galactose from digested food enter the glycolysis pathway. The entry point for fructose is dihydroxyacetone phosphate or glyceraldehyde-3-phosphate. The entry point for galactose is glucose, which enters in the form of glucose-6-phosphate.

23.76 Glycogen

23.78 It is important that the liver store glycogen because one of the functions of the liver is to maintain a relatively constant level of blood glucose. When the blood sugar levels are low, the liver can break down glycogen to release glucose. When the blood sugar levels are high, the liver can synthesize glycogen.

23.80 The liver has the enzymes necessary for glycogen breakdown.

23.82 The liver

23.84 Lactate (formed from pyruvate generated in the muscles), glycerol (derived from the hydrolysis of fats), and certain amino acids (from the amino acid pool).

23.86 The Cori cycle is the metabolic pathway in which lactate produced in the muscles is ultimately converted to glucose in the liver. As lactate levels increase in the muscle tissue, the lactate diffuses out of the tissue into the blood, where it is transported to the liver. An enzyme converts the lactate back into pyruvate, which is then converted to glucose by gluconeogenesis, and the glucose reenters the blood. The glucose goes to the muscle tissue via the blood.

Muscle activity quickly uses up stored ATP, and more energy must be produced by the breakdown of glycogen. Under normal aerobic conditions glycogenolysis produces glucose, which is further broken down into pyruvate that feeds into the citric acid cycle as acetyl CoA. The lactate pathway does not operate until oxygen supplies are limited, such as during intense muscular activity, and the anaerobic pathway that produces lactate is activated. The Cori cycle provides a mechanism for energy to be generated under anaerobic conditions, and returns an energy source (glucose) to the muscles.

23.88 There would be no lactate produced, so the Cori cycle wouldn't operate.

23.90 **a.** Insulin promotes the utilization of blood glucose, causing the level to decrease. Glucagon activates the breakdown of glycogen, thereby raising blood glucose levels.

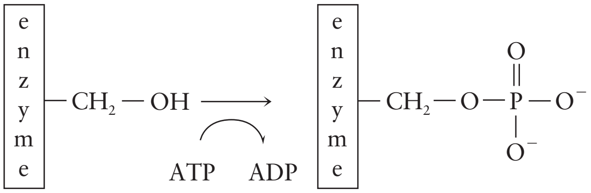
b. Insulin promotes glycogen formation, while glucagon stimulates the breakdown.

23.92 It is more important that epinephrine stimulate the breakdown of glycogen in the muscles rather than elevating blood sugar levels because it provides energy for a sudden burst of muscular activity. The entire body does not need a boost of blood sugar, only the muscles.

23.94 1.00×10^{24} ATP molecules

23.96 The removal of lactate from muscle cells shifts the equilibrium to the right, ensuring the regeneration of NAD^+ and the production of pyruvate by glycolysis. In the liver, pyruvate is used to make glucose, thus decreasing the pyruvate concentration, which shifts the equilibrium to the left and prevents the accumulation of lactate.

23.98



An ester linkage is formed.

Chapter 24

24.2 Glycerol, fatty acids, and monoglycerides

24.4 Chylomicrons are lipoprotein aggregates found in the lymph and the bloodstream.

24.6 The level of blood lipids rise within 2 hours of a meal, peaking approximately 4–6 hours after a meal rich in fat, then drops rather rapidly to a normal level.

24.8 LDL

24.10 Chylomicrons, VLDL, LDL, HDL

24.12 Fat mobilization is the process of hydrolyzing triglycerides to produce fatty acids and glycerol, both of which can be used for energy in muscle cells.

24.14 Storage of triglycerides

24.16 Fatty acids cannot serve as fuel for the brain because they cannot cross the blood–brain barrier.

24.18 Glycerol enters the glycolysis pathway as dihydroxyacetone phosphate.

24.20 One ATP

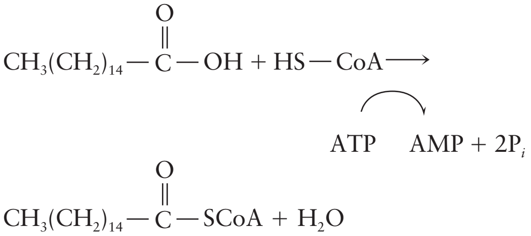
24.22 Glycerol can be converted to pyruvate and contribute to cellular energy production or be converted to glucose.

24.24 A fatty acid is first converted to a fatty acyl CoA, a high-energy compound. This occurs in the cytoplasm of the cell.

24.26 Two

24.28 FAD and NAD^+

24.30

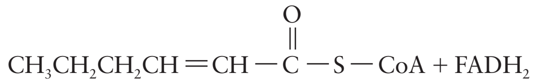


$$CH_3(CH_2)_{14}-\overset{\overset{\displaystyle O}{\|}}{C}-OH + HS-CoA \xrightarrow[\text{ATP} \quad \text{AMP} + 2P_i]{} CH_3(CH_2)_{14}-\overset{\overset{\displaystyle O}{\|}}{C}-SCoA + H_2O$$

24.32 The word *cycle* implies that the product is identical to the starting material, which is not the case. The fatty acyl product of a trip through the sequence has two fewer carbon atoms than the starting material.

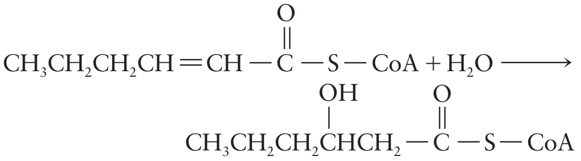
24.34 A 24-carbon fatty acid would yield 24/2, or 12 acetyl CoA molecules. Eleven trips through the spiral would be required, with the last trip producing two acetyl CoA molecules.

24.36 **a**.



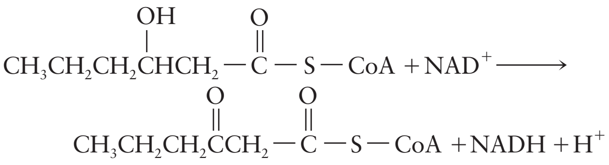
$$\mathrm{CH_3CH_2CH_2CH{=}CH{-}\overset{O}{\overset{\|}{C}}{-}S{-}CoA + FADH_2}$$

b.



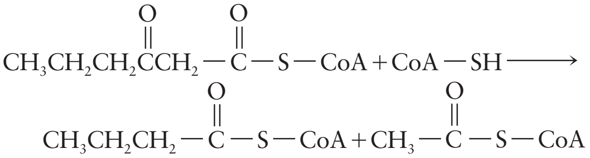
$$\mathrm{CH_3CH_2CH_2CH{=}CH{-}\overset{O}{\overset{\|}{C}}{-}S{-}CoA + H_2O \longrightarrow CH_3CH_2CH_2\overset{OH}{\overset{|}{C}}HCH_2{-}\overset{O}{\overset{\|}{C}}{-}S{-}CoA}$$

c.



$$\mathrm{CH_3CH_2CH_2\overset{OH}{\overset{|}{C}}HCH_2{-}\overset{O}{\overset{\|}{C}}{-}S{-}CoA + NAD^+ \longrightarrow CH_3CH_2CH_2\overset{O}{\overset{\|}{C}}CH_2{-}\overset{O}{\overset{\|}{C}}{-}S{-}CoA + NADH + H^+}$$

d.



$$\mathrm{CH_3CH_2CH_2\overset{O}{\overset{\|}{C}}CH_2{-}\overset{O}{\overset{\|}{C}}{-}S{-}CoA + CoA{-}SH \longrightarrow CH_3CH_2CH_2{-}\overset{O}{\overset{\|}{C}}{-}S{-}CoA + CH_3{-}\overset{O}{\overset{\|}{C}}{-}S{-}CoA}$$

24.38 10 ATP

24.40 Lipids are 25% more efficient than carbohydrates.

24.42 64 ATP molecules

24.44 Acetoacetate, β-hydroxybutyrate, and acetone.

24.46 The liver; the brain, heart, and skeletal muscles

24.48 In ketoacidosis, the kidneys excrete excessive amounts of water in response to the low blood pH.

24.50 Acid–base balance can be restored by using bicarbonate to neutralize the acids.

24.52 Two of the ketone bodies are carboxylic acids, which lower blood pH.

24.54 Fatty acids are built two carbons at a time and broken down two carbons at a time.

24.56 A transport system helps to move citrate from the mitochondria to the cytoplasm. In other words, there are molecules that assist the passage of citrate through the membrane.

24.58 ACP stands for acyl carrier protein

24.60 Two polyunsaturated fatty acids, linoleic and linolenic, cannot be synthesized by the body and yet are required for good health.

24.62 Amino acids serve the vital functions of providing building blocks for the synthesis of proteins in the body, being used to synthesize other nitrogen-containing biomolecules, and providing energy.

24.64 The sources of amino acids in the pool are digested dietary proteins, turnover of body proteins, and synthesis in the liver.

24.66 The percentage of amino acids used to synthesize proteins is 75%.

24.68 Purines and pyrimidines, heme, choline, ethanolamine

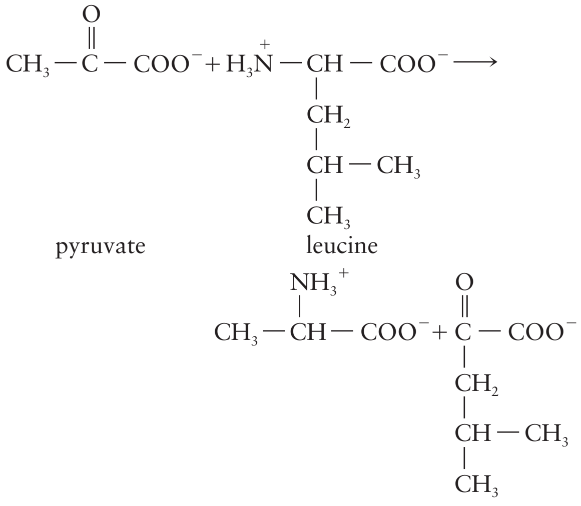
24.70 **a.** Transamination

b. Deamination

c. Transamination

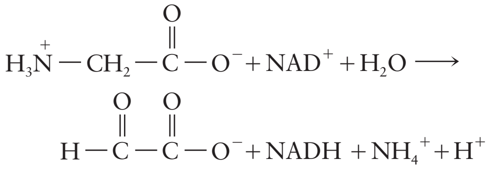
d. Transamination and deamination

24.72



$$\underset{\text{pyruvate}}{\mathrm{CH_3{-}\overset{O}{\overset{\|}{C}}{-}COO^-}} + \underset{\text{leucine}}{\mathrm{\overset{+}{H_3N}{-}\underset{\substack{|\\ CH_2\\ |\\ CH-CH_3\\ |\\ CH_3}}{CH}{-}COO^-}} \longrightarrow \mathrm{CH_3{-}\overset{NH_3^+}{\overset{|}{C}H}{-}COO^- + \overset{O}{\overset{\|}{\underset{\substack{|\\ CH_2\\ |\\ CH-CH_3\\ |\\ CH_3}}{C}}}{-}COO^-}$$

24.74

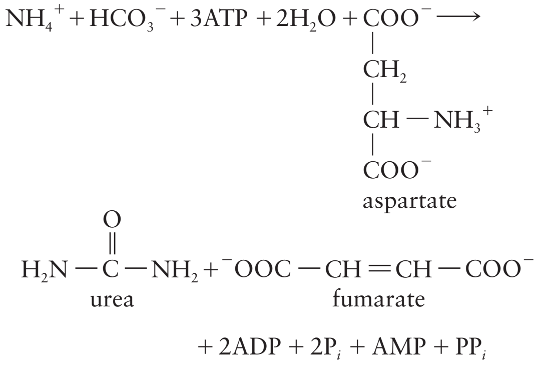


$$\mathrm{\overset{+}{H_3N}{-}CH_2{-}\overset{O}{\overset{\|}{C}}{-}O^- + NAD^+ + H_2O \longrightarrow H{-}\overset{O}{\overset{\|}{C}}{-}\overset{O}{\overset{\|}{C}}{-}O^- + NADH + NH_4^+ + H^+}$$

24.76 The liver

24.78 Carbamoyl phosphate

24.80



$$\mathrm{NH_4^+ + HCO_3^- + 3ATP + 2H_2O} + \underset{\text{aspartate}}{\mathrm{\underset{\substack{|\\ CH_2\\ |\\ CH-NH_3^+\\ |\\ COO^-}}{COO^-}}} \longrightarrow \underset{\text{urea}}{\mathrm{H_2N{-}\overset{O}{\overset{\|}{C}}{-}NH_2}} + \underset{\text{fumarate}}{\mathrm{{}^-OOC{-}CH{=}CH{-}COO^-}} + \mathrm{2ADP} + 2\mathrm{P}_i + \mathrm{AMP} + \mathrm{PP}_i$$

24.82 Yes; isoleucine, tryptophan, phenylalanine, and tyrosine

24.84 The lack of phenylalanine hydroxylase causes PKU.

24.86 During fasting or starvation, glucogenic amino acids are used to synthesize glucose through the process of gluconeogenesis after 12–18 hours without food.

24.88 The essential amino acid that makes tyrosine nonessential is phenylalanine.

24.90 An oxidation

24.92 Transaminases are used in the biosynthesis of amino acids and in the transfer of nitrogen atoms from amino acids when the disposal of nitrogen is necessary.

24.94 The glycolysis pathway and the citric acid cycle

24.96 Activation of zymogens and the production of new enzymes through induction

24.98 It is an LDL.

Chapter 25

25.2 Plasma and interstitial fluid

25.4 **a.** Intracellular fluid

b. Intracellular fluid

c. Plasma and interstitial fluid

d. Intracellular fluid

25.6 a. The principal cation in blood plasma is sodium, Na^+.

b. The principal cation in interstitial fluid is sodium, Na^+.

c. The principal cation in intracellular fluid is potassium, K^+.

25.8 The principle type of organic compound found in the intracellular fluid is protein.

25.10 Four of the reactions in the transport of O_2 and CO_2 are reversible and so are impacted by Le Châtelier's principle.

25.12 **a.** Formed when CO_2 combines with hemoglobin is carbaminohemoglobin.

b. The oxygen-transporting form of hemoglobin is oxyhemoglobin.

c. The form of hemoglobin designated as HHb is hemoglobin.

25.14 The reversible flow of chloride ions across the red blood cell membrane during the oxygen and carbon dioxide transport process is called the chloride shift.

25.16 A larger surface area increases the amount of O_2 and CO_2 that can diffuse through the surface. The partial pressure gradient is the force that causes O_2 and CO_2 movement.

25.18 **a.** Osmotic pressure

b. Blood pressure

25.20 Plasma proteins

25.22 Urea

25.24 The pH of urine is influenced by the foods we eat. The pH of urine is not as tightly regulated as that of the bloodstream.

25.26 Kidney damage, nephritis, bladder infection

25.28 Normal constituents are considered abnormal when they are eliminated in excess amounts.

25.30 Ingested liquids, water in foods, and water formed by catabolism contribute to the fluid intake of a human body.

25.32 Hyperventilation, excessive sweating, vomiting, diarrhea

25.34 Less water reabsorption, greater urine output

25.36 As fluid level decreases, saliva output decreases, giving the "thirst" feeling. Drinking water raises fluid level.

25.38 Blood buffers, urinary system, and respiratory system. The blood buffer system is the fastest to react.

25.40 Bicarbonate, phosphate, and protein

25.42 One component reacts with acid, and the other with base.

25.44 No. When the blood buffering systems become taxed, the respiratory and urinary systems act to help maintain blood pH.

25.46 $H_2PO_4^- + OH^- \rightarrow HPO_4^{2-} + H_2O$. This reaction absorbs excess OH^- ions and maintains pH. $HPO_4^{2-} + H_3O^+ \rightarrow H_2PO_4^- + H_2O$ This reaction absorbs excess H_3O^+ ions and maintains pH.

25.48 Hyperventilation is a symptom of low pH in the body (acidosis).

25.50 Respiratory alkalosis

25.52 CO_2 diffuses into the distal tubule cells to form carbonic acid, which then ionizes to H^+ and HCO_3^-. Thus, CO_2 concentration is lowered in the blood.

25.54 The buffer system in urine that keeps the urine pH from dropping lower than 6 is the phosphate buffer system.

25.56 The normal ratio of bicarbonate to carbonic acid in the blood is 20 parts of bicarbonate to 1 part of carbonic acid.

25.58 Hypoventilation causes respiratory acidosis.

Hyperventilation causes respiratory alkalosis.

25.60 Shallow breathing means that less CO_2 is exhaled. The concentration of carbonic acid in the bloodstream would increase.

25.62 Prolonged vomiting can lead to alkalosis because it decreases the acid concentration within the body. This raises the HCO_3^-/H_2CO_3 ratio above 20:1 and measurable alkalosis is observed.

25.64 The ultimate use for the O_2 in the cell is the formation of water. The O_2 that we inhale is not incorporated into the CO_2 that we exhale. The source of the CO_2 we exhale is acetyl CoA, the fuel of the citric acid cycle, which is derived from the digestion of macronutrients. The ultimate source of the CO_2 we exhale is, therefore, the carbon-containing organic compounds that our bodies use as fuels–carbohydrates, proteins, and fats.

25.66 Reaction (b) is not used in the human body as a buffer system because the pKa of H_3PO_4 is too low. The reaction occurs below normal body pH levels.

25.68 A hysterical individual might develop alkalosis because he or she is hyperventilating which causes too much carbon dioxide to be exhaled, which in turn disturbs the blood's normal carbon dioxide/carbonic acid ratio. In order to restore equilibrium, the concentration of carbonic acid will decrease and the blood pH will consequently increase, according to the related equilibria: $H_2O + CO_2 \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$. This can result in respiratory alkalosis.

25.70 Reducing the amount of water (solvent) means the solutes will become more concentrated.

25.72 Just as ionic and covalent compounds are electrically neutral, solutions of these substances would also be neutral.

25.74 The amino acid units of proteins have nitrogen-containing side chains that can react with acids; they also have acidic side chains that can react with bases.

25.76 All three blood buffering systems (proteins, phosphate, and bicarbonate/carbonic acid) are required and share the challenge of keeping blood pH within a narrow range. It is similar to an expensive piece of equipment having more than one safety feature.

25.78 Metabolic acidosis is a condition in which the body pH is too low. One mechanism for alleviating this is the increased excretion of H^+ ions in the urine. Since the ionic concentration of the urine is higher than normal, the osmotic pressure in the kidney tubules is higher and more water moves from the blood into the urine. This leads to greater volume of urine leaving the body, and consequently, a person suffering from metabolic acidosis might develop a thirst as a result of water loss through urination.

25.80 The concentration of hemoglobin of someone living in the Himalayas must be higher than that of someone living at a lower altitude because less oxygen is available in the air at high altitudes. More hemoglobin is produced to utilize the lower oxygen levels more efficiently.

25.82 During aerobic exercise, the body provides energy by respiration, which produces water as one of the byproducts. This water is eliminated in some way, even if perspiration does not occur. During exercise, the rate of respiration increases, causing the water to be lost more rapidly. Consequently, a person can dehydrate during aerobic exercise even without perspiring.

25.84 Uncontrolled diarrhea can lead to acidosis because the contents of the intestines are slightly alkaline. Uncontrolled diarrhea expels alkaline materials, requiring the body to replenish them. This in turn decreases the concentration of bicarbonate ions and increases the concentration of carbonic acid in the blood, thereby decreasing the blood pH.

APPENDIX C

Solutions to Learning Checks

Chapter 1

1.1 A change is chemical if new substances are formed and physical if no new substances are formed.

- **a.** Chemical: The changes in taste and odor indicate that new substances form.
- **b.** Physical: The handkerchief doesn't change, and the evaporated water is still water.
- **c.** Chemical: The changes in color and taste indicate that new substances form.
- **d.** Chemical: The gases and smoke released indicate that new substances form.
- **e.** Physical: The air is still air, as indicated by appearance, odor, and so on.
- **f.** Physical: On being condensed, the steam forms water, which is the same substance present before the change.

1.2

- **a.** Triatomic and heteroatomic: The three atoms of two kinds (oxygen and hydrogen) make it both triatomic (three atoms) and heteroatomic (two or more kinds of atoms).
- **b.** Triatomic and homoatomic: The three atoms make it triatomic, but all three atoms are the same (oxygen).
- **c.** Polyatomic and heteroatomic: The total of five atoms makes it polyatomic, and the two different kinds of atoms (carbon and hydrogen) make it heteroatomic.

1.3 Molecules of elements can be diatomic, triatomic, or polyatomic, but all atoms will be identical and will be represented by the same color. Molecules of compounds must be diatomic, triatomic, or polyatomic (more than one atom), and the atoms will not all be identical.

- **a.** Compound: polyatomic and heteroatomic
- **b.** Element: diatomic and homoatomic
- **c.** Element: polyatomic and homoatomic
- **d.** Compound: polyatomic and heteroatomic

1.4 The product would have to be a compound because it would be polyatomic (more than one atom because two substances were used) and heteroatomic (different atoms from the two different substances).

1.5 Substitute the given radius and π values into the equation:

$$A = \pi r^2 = (3.14)(3.5\ \text{cm})^2 = (3.14)(12.25\ \text{cm}^2) = 38\ \text{cm}^2$$

1.6 Because 1 kg = 1000 g,

$$0.819\ \cancel{\text{kg}} \times \frac{1000\ \text{g}}{1\ \cancel{\text{kg}}} = 819\ \text{g}$$

1.7 Use Equation 1.4 and the fact that 77°F = 25°C, as shown in Example 1.7.

$$\text{K} = {}^\circ\text{C} + 273 = 25^\circ\text{C} + 273 = 298\ \text{K}$$

1.8

- **a.** Scientific notation is used. In nonscientific notation, the number is written 588.
- **b.** Scientific notation is not used. In scientific notation, the number is written 4.39×10^{-4}.
- **c.** Scientific notation is used. In nonscientific notation, the number is written 0.0003915.
- **d.** Scientific notation is not used. In scientific notation, the number is written 9.870×10^{3}.
- **e.** Scientific notation is not used. In scientific notation, the number is written 3.677×10^{1}.
- **f.** Scientific notation is not used. In scientific notation, the number is written 1.02×10^{-1}.

1.9 The two important things to note are the placement of the decimal in the standard position and the correct value of the exponent.

- **a.** Written incorrectly: The decimal is not in standard position. Move the decimal 1 place to the left and increase the exponent by 1 to account for moving the decimal: 6.25×10^{5}.
- **b.** Written incorrectly: The decimal is not in the standard position, and no exponent is used. Move the decimal 3 places to the right and use -3 for the exponent to account for moving the decimal: 9.8×10^{-3}.
- **c.** Written incorrectly: The decimal is not in the standard position. Move the decimal 3 places to the right and reduce the exponent by 3 to account for moving the decimal: 4.1×10^{-6}.
- **d.** Written correctly.

1.10 Perform multiplications and divisions separately for the nonexponential and exponential terms, then combine the results into the final answer.

- **a.** $(2.4 \times 10^{3})(1.5 \times 10^{4}) = (2.4 \times 1.5)(10^{3} \times 10^{4}) = (3.6)(10^{3+4}) = 3.6 \times 10^{7}$
- **b.** $(3.5 \times 10^{2})(2.0 \times 10^{-3}) = (3.5 \times 2.0)(10^{2} \times 10^{-3}) = (7.0)(10^{2+(-3)}) = 7.0 \times 10^{-1}$
- **c.** $$\frac{6.3 \times 10^{5}}{2.1 \times 10^{3}} = \left(\frac{6.3}{2.1}\right)\left(\frac{10^{5}}{10^{3}}\right) = (3.0)(10^{5-3})$$ $$= 3.0 \times 10^{2}$$
- **d.** $$\frac{4.4 \times 10^{-2}}{8.8 \times 10^{-3}} = \left(\frac{4.4}{8.8}\right)\left(\frac{10^{-2}}{10^{-3}}\right) = (.50)(10^{-2-(-3)})$$ $$= .50 \times 10^{1} = 5.0 \times 10^{0}, \text{ or } 5.0$$

1.11 The primary challenge is to interpret correctly the significance of zeros. Leading zeros to the left of nonzero numbers are not significant. Trailing zeros are significant only when a decimal is present; all zeros between non-zero digits are significant.

- **a.** 2, trailing zero is not significant.
- **b.** 4

c. 3, leading zeros are not significant.

d. 2

e. 1, leading zeros are not significant.

f. 4, trailing zero is significant.

1.12 **a.** 3 significant figures; original decimal position is 2 places to the right of standard position, so exponent is +2. 1.01×10^2 m.

b. 2 significant figures; original decimal position is 3 places to the right of standard position, so exponent is +3. 1.2×10^3 g.

c. 3 significant figures; original decimal position is 3 places to the left of standard position, so exponent is −3. 2.30×10^{-3} kg.

d. 4 significant figures; original decimal position is 3 places to the right of standard position, so exponent is +3. 1.296×10^{3}°C.

e. 4 significant figures; original decimal position is 1 place to the right of standard position, so exponent is +1. 2.165×10^1 mL.

f. 2 significant figures; original decimal position is 2 places to the left of standard position, so exponent is −2. 1.5×10^{-2} km.

1.13 **a.** Answer will be rounded to 2 significant figures to match 0.0019.

$$(0.0019)(21.39) = 0.04064 = 4.1 \times 10^{-2}$$

b. Answer will be rounded to 2 significant figures to match 4.1.

$$\frac{8.321}{4.1} = 2.0295 = 2.0$$

c. Answer will be rounded to 3 significant figures to match 0.0911 and 3.22.

$$\frac{(0.0911)(3.22)}{(1.379)} = 0.21272 = 0.213, \text{ or } 2.13 \times 10^{-1}$$

1.14 In each case, the sum or difference is rounded to have the same number of places to the right of the decimal as the least number of places in the terms added or subtracted.

a. Answer will be rounded to have one place to the right of the decimal to match 3.2.

$$8.01 + 3.2 = 11.21 = 11.2$$

b. Answer will be rounded to have no places to the right of the decimal to match 3000.

$$3000. + 20.3 + 0.009 = 3020.309 = 3020$$

c. Answer will be rounded to have two places to the right of the decimal to match both 4.33 and 3.12.

$$4.33 - 3.12 = 1.21$$

d. Answer will be rounded to have two places to the right of the decimal to match 2.42.

$$6.023 - 2.42 = 3.603 = 3.60$$

1.15 Two factors result from the relationship 1 g = 1000 mg. The factors are:

$$\frac{1\text{ g}}{1000\text{ mg}} \quad \text{and} \quad \frac{1000\text{ mg}}{1\text{ g}}$$

The first factor is used because it cancels the mg unit and generates the g unit:

Step 1. 1.1 mg

Step 2. 1.1 mg = g

Step 3. $1.1\,\cancel{\text{mg}} \times \dfrac{1\text{ g}}{1000\,\cancel{\text{mg}}} = \text{g}$

Step 4. $\dfrac{(1.1)(1\text{ g})}{(1000)} = 0.0011\text{ g} = 1.1 \times 10^{-3}\text{ g}$

The number of significant figures matches the number in 1.1 because the 1 and 1000 are exact numbers.

1.16 Two factors, 1 km/1000 m and 0.621 mi/1 km, are used to convert meters to miles, and two factors, 60 s/1 min and 60 min/1 h, are used to convert seconds in the denominator to hours.

$$10.0\,\frac{\cancel{\text{m}}}{\cancel{\text{s}}} \times \frac{1\,\cancel{\text{km}}}{1000\,\cancel{\text{m}}} \times \frac{0.621\text{ mi}}{1\,\cancel{\text{km}}} \times \frac{60\,\cancel{\text{s}}}{1\,\cancel{\text{min}}} \times \frac{60\,\cancel{\text{min}}}{1\text{ h}} = 22.356\text{ mi/h}$$

1.17 Debra lost 17 lb.

$$\text{Percent} = \frac{\textit{part}}{\textit{total}} \times 100 = \frac{17\ \textit{lb}}{184\ \textit{lb}} \times 100 = 9.2\%$$

1.18 **a.** $\% = \dfrac{\text{part}}{\text{total}} \times 100;\ \% = \dfrac{\$988}{\$1200} \times 100 = 82.3\%$

b. $\% = \dfrac{\text{part}}{\text{total}} \times 100$

$$90.4\% = \frac{\text{part}}{83} \times 100$$

$$\frac{(90.4\%)(83)}{100} = \text{part}$$

= No. voting to not take final

= 75.0

Number voting to take exam = 83 − 75 = 8.

1.19 **a.** Density (d) $= \dfrac{m}{V} = \dfrac{1.04\ g}{1\ mL}$

The volume is 1.20 L or 1200 mL

$$\text{d} = \frac{m}{V} \text{ or m} = (\text{d})(\text{V})$$

$\text{m} = \dfrac{1.04\ g}{1\ \cancel{mL}} \times 1200\ \cancel{\text{mL}} = 1248$ g or 1250 g (three significant figures)

b. The sample mass is 98.5 g, and we wish to convert this to cm^3. The second factor given above will work.

$$98.5\ \cancel{g} \times \frac{1.0\text{ cm}^3}{2.7\ \cancel{g}} = 36.48\text{ cm}^3 \text{ (calculator answer)}$$

$$= 3.6 \times 10^1\text{ cm}^3 \text{ (properly rounded answer)}$$

1.20 **a.** The sample mass is equal to the difference between the mass of the container with the sample inside and the mass of the empty container:

$$m = 64.93\text{ g} - 51.22\text{ g} = 13.71\text{ g}$$

The density of the sample is equal to the sample mass divided by the sample volume:

$$d = \frac{m}{V} = \frac{13.71\text{ g}}{10.00\text{ mL}}$$

$$= 1.371\text{ g/mL (properly rounded answer)}$$

b. The identity can be determined by calculating the density of the sample from the data and comparing the density with the known densities of the two possible metals. The volume of the sample is equal to the difference between the cylinder readings with the sample present and with the sample absent:

$$V = 25.2\text{ mL} - 21.2\text{ mL} = 4.0\text{ mL}$$

According to Table 1.3, 1 mL = 1 cm^3, so the sample volume is equal to 4.0 cm^3. The density of the sample is equal to the sample mass divided by the sample volume:

$$d = \frac{m}{V} = \frac{35.66\text{ g}}{4.0\text{ cm}^3}$$

$$= 8.9\text{ g/cm}^3\text{ (properly rounded answer)}$$

A comparison with the known densities of nickel and chromium allows the metal to be identified as nickel.

Chapter 2

2.1 The number of atoms in each molecule is represented by a subscript in the formula.

a. H_3PO_4 b. SO_3 c. $C_6H_{12}O_6$

2.2 **a.** The atomic number, Z, equals the number of protons: $Z = 4$. The mass number, A, equals the sum of the number of protons and the number of neutrons: $A = 4 + 5 = 9$. According to the periodic table, the element with an atomic number of 4 is beryllium, with the symbol Be. The isotope symbol is ${}^{9}_{4}\text{Be}$.

b. According to the periodic table, chlorine has the symbol Cl and an atomic number, Z, of 17. The mass number, 37, is equal to the sum of the number of protons and neutrons: $A = \#p + \#n$. Therefore, the number of neutrons is equal to the mass number, A, minus the number of protons: $\#n = A - 17 = 37 - 17 = 20$.

c. According to the periodic table, the element with the symbol Si is silicon, which has an atomic number of 14. Therefore, the atom contains 14 protons. Since $A = \#p + \#n$, we see that $\#n = A - \#p = 28 - 14 = 14$.

2.3 **a.** Nitrogen atoms have a periodic table weight of 14.01 u, which rounds to 14 u. Iron atoms have a periodic table weight of 55.85 u, which rounds to 56 u. Thus, four nitrogen atoms (4 × 14 u = 56 u) will balance one iron atom.

b. Carbon atoms have a periodic table weight of 12.01 u, which rounds to 12 u. Helium atoms have a periodic table weight of 4.00 u, which rounds to 4 u. Thus, two carbon atoms (2 × 12 u = 24 u) will balance six helium atoms (6 × 4 u = 24 u).

c. Calcium atoms have a periodic table weight of 40.08 u, which rounds to 40 u. Argon atoms have a periodic table weight of 39.95 u, which rounds to 40 u. Thus, two calcium atoms (2 × 40 u = 80 u) will balance two argon atoms (2 × 40 u = 80 u).

2.4 Molecular weights are obtained by adding the atomic weights of the atoms in molecules. We have used four significant figures in atomic weights.

a. H_2SO_4; molecular weight = 2(at. wt. H) + (at. wt. S) + 4(at. wt. O)

$$\begin{aligned} \text{MW} &= 2(1.008\text{ u}) + 32.06\text{ u} + 4(16.00\text{ u}) \\ &= 2.016\text{ u} + 32.06\text{ u} + 64.00\text{ u} \\ &= 98.08\text{ u} \end{aligned}$$

b. C_3H_8O; molecular weight = 3(at. wt. C) + 8(at. wt. H) + (at. wt. O)

$$\begin{aligned} \text{MW} &= 3(12.01\text{ u}) + 8(1.008\text{ u}) + 16.00\text{ u} \\ &= 36.03\text{ u} + 8.064\text{ u} + 16.00\text{ u} \\ &= 60.09\text{ u} \end{aligned}$$

2.5 **a.** Because naturally occurring fluorine consists of only a single isotope, the equation for calculating atomic weight becomes:

$$\text{At. wt.} = \frac{(\%\text{ fluorine-19})(\text{mass fluorine-19})}{100}$$

$$= \frac{(100)(19.00\text{ u})}{100} = 19.00\text{ u}$$

The calculated value is the same as the periodic table value.

b.

$$\text{At. wt.} = \frac{(\%\text{ Mg-24})(\text{mass Mg-24})}{100}$$

$$+ \frac{(\%\text{ Mg-25})(\text{mass Mg-25}) + (\%\text{ Mg-26})(\text{mass Mg-26})}{100}$$

$$= \frac{(78.70)(23.99\text{ u}) + (10.13)(24.99\text{ u})}{100}$$

$$\frac{+ (11.17)(25.98\text{ u})}{100}$$

$$= 24.31\text{ u}$$

Once again, the calculated value is the same as the periodic table value.

2.6 The mass ratio is obtained by dividing the mass of the magnesium sample by the mass of the carbon sample:

$$\frac{\text{Mg mass}}{\text{C mass}} = \frac{13.66\text{ g}}{6.748\text{ g}} = 2.024$$

The number of atoms in each sample is calculated using the factors obtained earlier from the mass of one atom of each element:

$$13.66\ \cancel{\text{g}}\ \cancel{\text{Mg}} \times \frac{1\text{ Mg atom}}{4.037 \times 10^{-23}\ \cancel{\text{g}}\ \cancel{\text{Mg}}}$$

$$= 3.384 \times 10^{23}\text{ Mg atoms}$$

$$6.748\ \cancel{\text{g}}\ \cancel{\text{C}} \times \frac{1\text{ C atom}}{1.994 \times 10^{-23}\ \cancel{\text{g}}\ \cancel{\text{C}}} = 3.384 \times 10^{23}\text{ C atoms}$$

2.7 **a.** Step 1: 98.6 g S

Step 2: $98.6\ \text{g S} \qquad = \qquad \text{mol S}$

Step 3: $98.6\ \text{g S} \times \frac{1\ \textit{mol S}}{32.06\ \textit{g S}} = \qquad \text{mol S}$

Step 4: $98.6\ \cancel{\text{g S}} \times \frac{1\ \textit{mol S}}{32.06\ \cancel{\textit{g S}}} = 3.08\ \text{mol S}$

b. Step 1: 1 atom S

Step 2: $1\ \text{atom S} \qquad = \qquad \text{g}$

Step 3: $1\ \text{atom S} \times \frac{32.06\ \textit{g S}}{6.02 \times 10^{23}\ \textit{atms S}} = \qquad \text{g}$

Step 4: $1\ \cancel{\text{atom S}} \times \frac{32.06\ \textit{g S}}{6.02 \times 10^{23}\ \cancel{\textit{atms S}}} = 5.33 \times 10^{-23}\ \text{g}$

2.8 **a.** Step 1: 63.9 g CO_2

Step 2: $63.9\ \text{g CO}_2 \qquad = \qquad \text{mol CO}_2$

Step 3: $63.9\ \text{g CO}_2 \times \frac{1\ \textit{mol CO}_2}{44.01\ \textit{g CO}_2} = \qquad \text{mol CO}_2$

Step 4: $63.9\ \cancel{\text{g CO}_2} \times \frac{1\ \textit{mol CO}_2}{44.01\ \cancel{\textit{g CO}_2}} = 1.45\ \text{mol CO}_2$

b. Step 1: 1 mc CO_2

Step 2: $1\ \text{mc CO}_2 \qquad = \text{g CO}_2$

Step 3: $1\ \text{mc CO}_2 \times \frac{44.01\ \textit{g CO}_2}{6.02 \times 10^{23}\ \textit{mc CO}_2} = \text{g CO}_2$

Step 4: $1\ \cancel{\text{mc CO}_2} \times \frac{44.01\ \textit{g CO}_2}{6.02 \times 10^{23}\ \cancel{\textit{mc CO}_2}}$

$= 7.31 \times 10^{-23}\ \text{g CO}_2$

2.9 The relationships between moles of atoms in 1 mol of molecules is given by the subscripts of the atoms. Thus, 1 mol of glucose molecules would contain 6 mol of C atoms, 12 mol of H atoms, and 6 mol of O atoms. One-half mol of glucose molecules would contain half as many moles of each atom, or 3 mol of C atoms, 6 mol of H atoms, and 3 mol of O atoms.

2.10 $\% = \frac{\text{part}}{\text{total}} \times 100$

In each compound, the part will be the mass of carbon associated with some mass of compound (the total). The mass relationships are easily obtained by assuming a sample size equal to 1.00 mol of each compound.

CO_2: 1.00 mol CO_2 molecules = 1.00 mol C atoms + 2.00 mol O atoms or, using atomic weights,

$$44.01\ \text{g CO}_2 = 12.01\ \text{g C} + 32.00\ \text{g O}$$

$$\%\ \text{C} = \frac{(12.01\ \text{g C}) \times 100}{(44.01\ \text{g CO}_2)} = 27.29\%\ \text{C}$$

CO: 1.00 mol CO molecules = 1.00 mol C atoms + 1.00 mol O atoms

$$28.01\ \text{g CO} = 12.01\ \text{g C} + 16.00\ \text{g O}$$

$$\%\ \text{C} = \frac{(12.01\ \text{g C})}{(28.01\ \text{g CO})} \times 100 = 42.88\%\ \text{C}$$

Chapter 3

3.1 Each element is found at the intersection of the given group (vertical columns) and period (horizontal rows).

a. Ge **b.** Re

3.2 **a.** Period 1 has 2 elements, H and He.

b. Group IIB(12) has 4 elements, Zn, Cd, Hg, and Cn.

3.3 **a.** The maximum number of electrons that can be found in any orbital, including a 4*p* orbital, is 2.

b. All *d* subshells, including the 5*d*, contain 5 orbitals with a capacity of 2 electrons each. Thus, the 5*d* subshell can contain a maximum of 10 electrons.

c. Shell number 1 contains only a single *s* orbital, the 1*s* orbital, and so can contain a maximum of 2 electrons.

3.4 The valence shell is the last shell with electrons. According to Table 3.2, group VA(15) elements all have 5 electrons in the valence shell. Group VIA(16) elements have 6, group VIIA(17) have 7, and the noble gases VIIIA(18) have 8.

3.5 **a.** Strontium (Sr) is in group IIA(2) and so contains 2 electrons in its valence shell.

b. Once again, the roman numeral of the group heading gives the number of valence-shell electrons. The element is Ge, and because it is in group IVA(14), it has 4 electrons in the valence shell.

c. The fifteenth element in period 4 is As, which is in group VA(15) and therefore has 5 electrons in the valence shell.

3.6 The subshell filling order is obtained from Figure 3.7 or Figure 3.8. All subshells except the last one are filled to their capacities as follows: *s* subshells—filled with 2, *p* subshells—filled with 6, *d* subshells—filled with 10, and *f* subshells—filled with 14. The last subshell has only enough electrons added to bring the total number of electrons to the desired value.

a. Element 9 requires 9 electrons: $1s^22s^22p^5$; 1 unpaired

b. Mg is element 12 and so needs 12 electrons:

$1s^22s^22p^63s^2$; 0 unpaired

c. The element in group VIA(16) and period 3 is S, which is element 16. Therefore, it needs 16 electrons:

$1s^22s^22p^63s^23p^4$; 2 unpaired

d. An atom with 23 protons needs 23 electrons:

$1s^22s^22p^63s^23p^64s^23d^3$; 3 unpaired

3.7 **a.** From Learning Check 3.6, the electronic configuration of element number 9 is $1s^22s^22p^5$. The $1s^2$ electrons represent the configuration of helium. So, we can write the configuration as $[\text{He}]2s^22p^5$.

b. The configuration of Mg is $1s^22s^22p^63s^2$. The first 10 electrons represent the configuration of neon: $[\text{Ne}]3s^2$.

c. The configuration of S is $1s^22s^22p^63s^23p^4$. Once again, the first 10 electrons represent the configuration of neon: $[\text{Ne}]3s^23p^4$.

d. The 23 electrons are represented by $1s^22s^22p^63s^23p^64s^2$ $3d^3$. The first 18 electrons represent the configuration of argon: $[\text{Ar}]4s^23d^3$.

3.8 **a.** On the basis of the location of each element in Figure 3.9, the distinguishing electrons are of the following types: element 38(Sr): *s*; element 47(Ag): *d*; element 50(Sn): *p*; element 86(Rn): *p*.

b. Their classifications based on Figure 3.10 are element 38(Sr): representative element; element 47(Ag): transition element; element 50(Sn): representative element; element 86(Rn): noble gas.

3.9 The periodic table and Figure 3.12 are used.

a. Xe: nonmetal

b. As: metalloid

c. Hg: metal

d. Ba: metal

e. Th: metal

3.10 **a.** The slowest reaction involves Li, and the fastest involves K.

Li
Na
K

b. The rate of the reaction increases coming down the group, and according to Table 3.3, the ionization energy decreases coming down the group.

c. The decrease in ionization energy coming down the group means less energy is required to remove electrons from atoms of the elements located farther down the group. The reactions in Figure 3.17 involve the removal of an electron from atoms of the metals, so the easier it is to remove electrons (less energy required), the faster the reaction should go. This trend in speed is what is observed.

Chapter 4

4.1 The subshell filling order is obtained from Figure 3.7 or Figure 3.8.

F; 9 electrons: $1s^22s^22p^5$

K; 19 electrons: $1s^22s^22p^63s^23p^64s^1$

The configuration of F can be changed to that of He ($1s^2$) by giving up 7 electrons or to that of Ne ($1s^22s^22p^6$) by accepting 1 electron. The configuration of K can be changed to that of Ar ($1s^22s^22p^63s^23p^6$) by giving up 1 electron or to that of Kr ($1s^22s^22p^63s^23p^64s^23d^{10}4p^6$) by accepting 17 electrons.

4.2 **a.** Element number 9 is fluorine, which is in group VIIA(17) and so has 7 valence-shell electrons. The Lewis structure is $:\overset{\cdot\cdot}{\underset{\cdot\cdot}{\text{F}}}\cdot$.

b. Magnesium is in group IIA(2) and so has 2 valence-shell electrons. The Lewis structure is $\dot{\text{M}}\text{g}\cdot$.

c. Sulfur is in group VIA(16) and so has 6 valence-shell electrons. The Lewis structure is $:\overset{\cdot}{\underset{\cdot}{\text{S}}}\cdot$.

d. Krypton is a noble gas and so has 8 valence-shell electrons. The Lewis structure is $:\overset{\cdot\cdot}{\underset{\cdot\cdot}{\text{Kr}}}:$.

4.3 **a.** Lithium contains 3 electrons, with one of them classified as a valence-shell electron: $[\text{He}]2s^1$ and Li·.

b. Bromine contains 35 electrons, with 7 of them classified as valence-shell electrons: $[\text{Ar}]4s^23d^{10}4p^5$ and $:\overset{\cdot\cdot}{\underset{\cdot\cdot}{\text{Br}}}\cdot$.

c. Strontium contains 38 electrons, with 2 classified as valence-shell electrons: $[\text{Kr}]5s^2$ and $\dot{\text{S}}\text{r}\cdot$.

d. Sulfur contains 16 electrons, with 6 classified as valence-shell electrons: $[\text{Ne}]3s^23p^4$ and $:\overset{\cdot\cdot}{\underset{\cdot}{\text{S}}}\cdot$.

4.4 The change that will actually take place is the one that involves the fewest electrons. Thus, F will gain 1 electron rather than give up 7, and K will give up 1 electron rather than gain 17:

$$\text{F} + 1e^- \rightarrow \text{F}^-$$

$$\text{K} \rightarrow \text{K}^+ + 1e^-$$

4.5 **a.** Element number 34 is a nonmetal. It is in group VIA(16) and will, when treated using the rules for nonmetals, accept 8 − 6 or 2 electrons during ionic bond formation:

$$\text{Se} + 2e^- \rightarrow \text{Se}^{2-}$$

b. Rb, a metal in group IA(1), will lose 1 electron during ionic bond formation:

$$\text{Rb} \rightarrow \text{Rb}^+ + 1e^-$$

c. Element 18 is a nonmetallic noble gas. It will not react to form ionic bonds.

d. In, a metal in group IIIA(13), will lose 3 electrons during ionic bond formation:

$$\text{In} \rightarrow \text{In}^{3+} + 3e^-$$

4.6 **a.** Mg, a metal in group IIA(2), will lose 2 electrons:

$$\text{Mg} \rightarrow \text{Mg}^{2+} + 2e^-$$

O, a nonmetal in group VIA(16), will gain 2 electrons:

$$\text{O} + 2e^- \rightarrow \text{O}^{2-}$$

The positive and negative ions are combined in the lowest numbers possible to give the compound formula. The combining requirement is that the total number of positive charges from the positive ion must equal the total number of negative charges from the negative ion. In the case of Mg^{2+} and O^{2-}, one of each ion satisfies the requirement, and the formula is MgO.

b. K, a group IA(1) metal, will lose 1 electron:

$$\text{K} \rightarrow \text{K}^+ + 1e^-$$

S, a group VIA(16) nonmetal, will gain 2 electrons:

$$\text{S} + 2e^- \rightarrow \text{S}^{2-}$$

In the formula, 2K^+ will be needed for each S^{2-}. Thus, the compound formula is K_2S.

c. Ca, a group IIA(2) metal, will lose 2 electrons:

$$\text{Ca} \rightarrow \text{Ca}^{2+} + 2e^-$$

Br, a group VIIA(17) nonmetal, will gain 1 electron:

$$\text{Br} + 1e^- \rightarrow \text{Br}^-$$

In the formula, 2Br^- will combine with each Ca^{2+}: CaBr_2

4.7 **a.** Magnesium oxide

b. Potassium sulfide

c. Calcium bromide

4.8 **a.** Charge balance requires that 2Br^- combine with each Co^{2+}: CoBr_2. Names are cobalt(II) bromide and cobaltous bromide.

b. Charge balance requires that 3Br^- combine with each Co^{3+}: CoBr_3. Names are cobalt(III) bromide and cobaltic bromide.

4.9 **a.** For H_2S, the molecular weight is the sum of the atomic weights of the atoms in the formula:

$$\begin{aligned} MW &= (2)(\text{at. wt. H}) + (1)(\text{at. wt. S}) \\ &= (2)(1.01\text{ u}) + (1)(32.1\text{ u}) \\ MW &= 34.1\text{ u} \end{aligned}$$

For CaO, the formula weight is also equal to the sum of the atomic weights of the atoms in the formula:

$$\begin{aligned} FW &= (1)(\text{at. wt. Ca}) + (1)(\text{at. wt. O}) \\ &= (1)(40.1\text{ u}) + (1)(16.0\text{ u}) \\ FW &= 56.1\text{ u} \end{aligned}$$

b. According to Section 2.6, 1.00 mol of a molecular compound has a mass in grams equal to the molecular weight of the compound. Thus, 1.00 mol H_2S = 34.1 g H_2S. For ionic compounds, 1.00 mol of compound has a mass in grams equal to the formula weight of the compound. Thus, 1.00 mol CaO = 56.1 g CaO.

c. In Section 2.6, we learned that 1.00 mol of a molecular compound contains Avogadro's number of molecules. Thus, 1.00 mol $H_2S = 6.02 \times 10^{23}$ molecules of H_2S. In the case of ionic compounds, 1.00 mol of compound contains Avogadro's number of formula units. That is, 1.00 mol of calcium oxide contains Avogadro's number of CaO units, where each unit represents one Ca^{2+} ion and one O^{2-} ion. Thus:

$$1.00\text{ mol CaO} = 6.02 \times 10^{23}\text{ CaO units} \qquad \text{or}$$

$$\begin{aligned} 1.00\text{ mol CaO} &= 6.02 \times 10^{23}\ Ca^{2+}\text{ ions} \\ &\quad + 6.02 \times 10^{23}\ O^{2-}\text{ ions} \end{aligned}$$

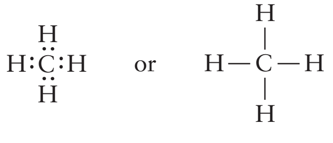
4.10 **a.** N is in group VA(15) and therefore has 5 valence-shell electrons. Two N atoms will provide 10 total electrons to satisfy the octets. At least 2 electrons are needed to bond the atoms. This leaves only 8 electrons to satisfy the remaining octet requirements of both atoms. This deficiency of electrons means some multiple bonds will be needed between the atoms:

$$:\dot{\underset{\cdot}{N}}\cdot + \cdot\dot{\underset{\cdot}{N}}: \longrightarrow :N:::N: \qquad \text{or} \qquad N\equiv N$$

b. Br is in group VIIA(17) and therefore has 7 valence-shell electrons. Two atoms will provide 14 electrons, and the bonding is readily shown:

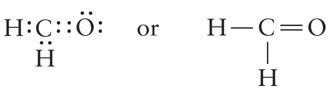
$$:\ddot{\underset{\cdot\cdot}{Br}}\cdot + \cdot\ddot{\underset{\cdot\cdot}{Br}}: \longrightarrow :\ddot{\underset{\cdot\cdot}{Br}}:\ddot{\underset{\cdot\cdot}{Br}}: \qquad \text{or} \qquad Br-Br$$

4.11 **a.** Each C contributes 4 valence-shell electrons, and each H contributes 1. The total available is 8:



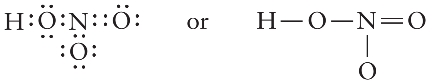
$$\begin{matrix} & H & \\ H & \!:\!\ddot{\underset{\cdot\cdot}{C}}\!:\! & H \\ & H & \end{matrix} \quad \text{or} \quad \begin{matrix} & H & \\ & | & \\ H- & C & -H \\ & | & \\ & H & \end{matrix}$$

b. Each H contributes 1 electron, the C contributes 4, and the O contributes 6. The total of 12 electrons cannot satisfy all octets unless two pair are shared between the C and O atoms:



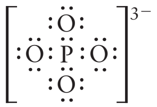
$$H\!:\!\underset{\underset{H}{\cdot\cdot}}{C}\!::\!\ddot{O}\!: \quad \text{or} \quad \begin{matrix} H-C=O \\ | \\ H \end{matrix}$$

c. Each H contributes 1 electron, each O contributes 6, and the N contributes 5. The 24 total electrons can satisfy all octets only if two pair are shared between the N and one of the O atoms:



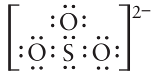
$$H\!:\!\ddot{\underset{\cdot\cdot}{O}}\!:\!\underset{\underset{:\ddot{\underset{\cdot\cdot}{O}}:}{\cdot\cdot}}{N}\!::\!\ddot{O}\!: \quad \text{or} \quad \begin{matrix} H-O-N=O \\ \quad\quad\ \ | \\ \quad\quad\ \ O \end{matrix}$$

4.12 **a.** The P provides 5 electrons, each O provides 6, and the 3− charge indicates an additional 3 electrons. The total number of electrons is therefore 32, which is enough to satisfy all octets without any multiple bonds:



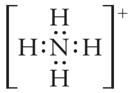
$$\left[\begin{matrix} & :\ddot{O}: & \\ :\ddot{\underset{\cdot\cdot}{O}}: & \underset{\cdot\cdot}{\ddot{P}} & :\ddot{\underset{\cdot\cdot}{O}}: \\ & :\ddot{\underset{\cdot\cdot}{O}}: & \end{matrix}\right]^{3-}$$

b. The S provides 6 electrons, each O provides 6, and the 2− charge indicates an additional 2 electrons. The total number of electrons is therefore 26, which is enough to satisfy all octets without any multiple bonds:



$$\left[\begin{matrix} & :\ddot{O}: & \\ :\ddot{\underset{\cdot\cdot}{O}}: & \underset{\cdot\cdot}{\ddot{S}} & :\ddot{\underset{\cdot\cdot}{O}}: \end{matrix}\right]^{2-}$$

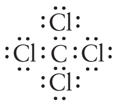
c. The N provides 5 electrons, each H provides 1, and the + charge indicates that 1 must be subtracted. The total number of electrons is therefore 8, which is enough to satisfy the octet of N, and each H requirement of 2 electrons without any multiple bonds:



$$\left[\begin{matrix} & H & \\ H & \!:\!\ddot{\underset{\cdot\cdot}{N}}\!:\! & H \\ & H & \end{matrix}\right]^{+}$$

4.13 **a.** The 3 electron pairs around the B atom will arrange themselves in a flat triangle around the B. Therefore, the molecule will be flat (planar) with the F atoms forming a triangle around the B.

b. The Lewis structure is:



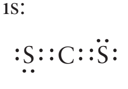
$$\begin{matrix} & :\ddot{Cl}: & \\ :\ddot{\underset{\cdot\cdot}{Cl}}: & \underset{\cdot\cdot}{\ddot{C}} & :\ddot{\underset{\cdot\cdot}{Cl}}: \\ & :\ddot{\underset{\cdot\cdot}{Cl}}: & \end{matrix}$$

The 4 electron pairs around the C atom will arrange themselves in a tetrahedral orientation. Thus, the molecule will be tetrahedral with C in the center and a Cl atom at each of the corners of the tetrahedron around the C.

c. The Lewis structure is:

$$:\ddot{\underset{\cdot\cdot}{O}}:\ddot{S}::\ddot{O}:$$

The 3 electron pairs around the S will occupy the corners of a triangle around the S. This will give rise to a bent molecule



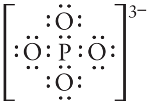
d. The Lewis structure is:

$$:\underset{\cdot\cdot}{S}::C::\ddot{S}:$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

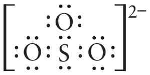
Each double bond on the central C atom is treated like a single pair of electrons when VSEPR theory is used. Thus, the double bonds are treated like 2 pairs and will arrange themselves to be on opposite sides of the C atom. A linear molecule results: S=C=S.

4.14 **a.** The Lewis structure from Learning Check 4.12 is:



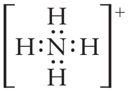
We see that phosphorus is the central atom, and it has four electron pairs around it. The four pairs will be located at the corners of a tetrahedron with the P in the middle. The four O atoms will occupy the corners of the tetrahedron, giving the same shape as that of the SO_4^{2-} ion of Example 4.14a.

b. The Lewis structure from Learning Check 4.12 is:



We see that sulfur is the central atom, and it has four electron pairs around it. The four pairs will be located at the corners of a tetrahedron with the S in the middle. The shape of the ion is determined by the location of the oxygen atoms and the S atom. The O atoms will occupy three of the corners of the tetrahedron, and one pair of electrons will occupy the fourth. Thus, the shape of the ion will be a triangular-based pyramid with the O atoms at the three corners of the base and the S atom at the top.

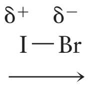
c. The Lewis structure from Learning Check 4.12 is:



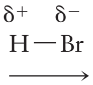
We see that nitrogen is the central atom, and it has four electron pairs around it. The four pairs will be located at the corners of a tetrahedron with the N in the middle. The four H atoms will thus be located at the corners of the tetrahedron with the N in the middle, giving a tetrahedral-shaped ion like the SO_4^{2-} ion of Example 4.14a.

4.15 **a.** No polarization because bound atoms are identical.

b. Br is located higher in the group and so is more electronegative than I:



c. Br is farther toward the right in the periodic table and so is more electronegative than H:



4.16 The values of ΔEN are used.

a. ΔEN = 4.0 − 0.8 = 3.2. Bond is classified as ionic.

b. ΔEN = 3.5 − 3.0 = 0.5. Bond is classified as polar covalent.

c. ΔEN = 3.0 − 1.5 = 1.5. Bond is classified as polar covalent.

d. ΔEN = 3.5 − 0.8 = 2.7. Bond is classified as ionic.

4.17 **a.** sulfur trioxide

b. boron trifluoride

c. disulfur heptoxide

d. carbon tetrachloride

4.18 **a.** Ca is a group IIA(2) metal and so forms Ca^{2+} ions. Formula: $CaHPO_4$; name: calcium hydrogen phosphate.

b. Mg is a group IIA(2) metal and so forms Mg^{2+} ions. Formula: $Mg_3(PO_4)_2$; name: magnesium phosphate.

c. K is a group IA(1) metal and so forms K^+ ions. Formula: $KMnO_4$; name: potassium permanganate.

d. The ammonium ion, NH_4^+, acts as the positive ion in this compound. Formula: $(NH_4)_2Cr_2O_7$; name: ammonium dichromate.

4.19 Assuming that dispersion forces are significant in establishing the melting and boiling points of these elements leads to the conclusion that, in each pair, the element with the higher atomic weight would have the higher melting and boiling points.

a. Se **b.** Sb **c.** Ne

Chapter 5

5.1 Both subscripts and coefficients are used.

N_2 : 2 atoms—on the basis of subscript.

$3H_2$: 6 atoms—on the basis of subscript and coefficient.

$2NH_3$: 2 N atoms (on the basis of coefficient) and 6 H atoms (on the basis of subscript and coefficient).

5.2 $2SO_2 + O_2 \rightarrow 2SO_3$

5.3 **a.** Oxygen is −2 (Rule 5).

Sulfur is +6 (Rule 6).

b. Calcium is +2 (Rule 3).

Oxygen is −2 (Rule 5).

Chlorine is +5 (Rule 6).

c. Oxygen is −2 (Rule 5).

Chlorine is +7 (Rule 7).

5.4 **a.** Zn = 0 (Rule 1), H^+ = +1 (Rule 2), Zn^{2+} = +2 (Rule 2), H_2 = 0 (Rule 1).

Zn is oxidized, so it is the reducing agent.

H^+ is reduced, so it is the oxidizing agent.

b. In KI: K = +1 (Rule 3), I = −1 (Rule 6).

Cl_2 = 0 (Rule 1).

In KCl: K = +1 (Rule 3), Cl = −1 (Rule 6).

I_2 = 0 (Rule 1).

I in KI is oxidized, so KI is the reducing agent.

Cl_2 is reduced, so Cl_2 is the oxidizing agent.

c. In IO_3-: O = −2 (Rule 5), I = +5 (Rule 7).

In HSO_3^-: H = +1 (Rule 4), O = −2 (Rule 5), S = +4 (Rule 7).

$I^- = -1$ (Rule 2).

In HSO_4^-: H = +1 (Rule 4), O = −2 (Rule 5), S = +6 (Rule 7).

S in HSO_3^- is oxidized, so HSO_3^- is the reducing agent.

I in IO_3^- is reduced, so IO_3^- is the oxidizing agent.

5.5 **a.** The O.N. of H changes from +1 to 0, and the O.N. of I changes from −1 to 0. Reaction is redox. Because one substance changes into two substances, the reaction is a decomposition.

b. The O.N. of H does not change. The O.N. of O changes from −1 (in a peroxide) to −2 (in water) and 0 (in O_2). This is an example in which the same element is both oxidized and reduced. The reaction is redox. Because one substance changes into two substances, the reaction is a decomposition.

c. No oxidation numbers change. The reaction is nonredox. This is a double-replacement (metathesis) reaction.

d. The O.N. of P changes from 0 to +5, and the O.N. of O changes from 0 to −2. The reaction is redox. Because two substances combine to form a single substance, the reaction is a combination.

e. The O.N. of Na does not change. The O.N. of I changes from −1 to 0, and the O.N. of Cl changes from 0 to −1. The reaction is redox. Because the Cl simply replaces the I in the compound, this is a single-replacement reaction.

5.6 **a.** Total ionic: $2Na^+(aq) + 2I^-(aq) + Cl_2(aq) \rightarrow 2Na^+(aq) + 2Cl^-(aq) + I_2(aq)$

Na^+ is a spectator ion.

Net ionic: $2I^-(aq) + Cl_2(aq) \rightarrow 2Cl^-(aq) + I_2(aq)$

b. Total ionic: $Ca^{2+}(aq) + 2Cl^-(aq) + 2Na^+(aq) + CO_3^{2-}(aq) \rightarrow 2Na^+(aq) + 2Cl^-(aq) + CaCO_3(s)$

Na^+ and Cl^- are spectator ions.

Net ionic: $Ca^{2+}(aq) + CO_3^{2-}(aq) \rightarrow CaCO_3(s)$

c. Total ionic: $Ba^{2+}(aq) + 2OH^-(aq) + 2H^+(aq) + SO_4^{2-}(aq) \rightarrow 2H_2O(\ell) + BaSO_4(s)$

There are no spectator ions, so the net ionic reaction is the same as the total ionic reaction.

5.7 **a.** 2. $1 \text{ mol } N_2(g) + 3 \text{ mol } H_2(g) \longrightarrow 2 \text{ mol } NH_3(g)$

3. $6.02 \times 10^{23}\ N_2 \text{ molecules} + 3(6.02 \times 10^{23})\ H_2 \text{ molecules} \longrightarrow 2(6.02 \times 10^{23})\ NH_3 \text{ molecules}$

4. $28.0\text{ g } N_2 + 3(2.00)\text{g } H_2 \longrightarrow 2(17.0)\text{g } NH_3$

b. **Step 1.** $2.11 \text{ mol } H_2$

Step 2. $2.11 \text{ mol } H_2 \qquad = \text{mol } NH_3$

Step 3. $2.11\ \cancel{\text{mol } H_2} \times \dfrac{2 \text{ mol } NH_3}{3\ \cancel{\text{mol } H_2}} = \text{mol } NH_3$

Step 4. $2.11 \times \dfrac{2 \text{ mol } NH_3}{3} = 1.406 \text{ mol } NH_3 = 1.41 \text{ mol } NH_3$

The answer was rounded to 3 significant figures to match the three in 2.11. The 2 and 3 are exact counting numbers.

c. **Step 1.** $9.47 \text{ g } H_2$

Step 2. $9.47 \text{ g } H_2 \qquad = \text{g } N_2$

Step 3. $9.47\ \cancel{\text{g } H_2} \times \dfrac{28.0 \text{ g } N_2}{6.00\ \cancel{\text{g } H_2}} = \text{g } N_2$

Step 4. $9.47 \times \dfrac{28.0 \text{ g } N_2}{6.00} = 44.19 \text{ g } N_2 = 44.2 \text{ g } N_2$

The answer was rounded to 3 significant figures to match the three in 9.47, 28.0 g N_2, and 6.00.

5.8 The mass of NH_3 possible from each reactant is calculated. The reactant giving the smallest mass of NH_3 is the limiting reactant, and the mass of NH_3 calculated for the limiting reactant is the amount that will be produced:

$$2.00\ \cancel{\text{mol } H_2} \times \frac{34.0 \text{ g } NH_3}{3\ \cancel{\text{mol } H_2}} = 22.7 \text{ g } NH_3$$

$$15.5\ \cancel{\text{g } N_2} \times \frac{34.0 \text{ g } NH_3}{28.0\ \cancel{\text{g } N_2}} = 18.8 \text{ g } NH_3$$

The results show the limiting reactant to be the 15.5 g of N_2, and the amount of NH_3 produced will be 18.8 g.

5.9 **a.**
$$\%\text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100$$
$$= \frac{17.43 \text{ g}}{21.34 \text{ g}} \times 100 = 81.68\%$$

b. The theoretical yield must be calculated.

$$510.\ \cancel{\text{g } CaCO_3} \times \frac{56.08 \text{ g CaO}}{100.1\ \cancel{\text{g } CaCO_3}} = 285.722 \text{ g CaO} = 286 \text{ g CaO}$$

The % yield is then calculated using this theoretical yield:

$$\%\text{ yield} = \frac{\text{actual yield}}{\text{theoretical yield}} \times 100$$
$$= \frac{235 \text{ g}}{286 \text{ g}} \times 100 = 82.2\%$$

Chapter 6

6.1 **a.**
$$d = \frac{\text{mass}}{\text{volume}}$$

$$\text{copper: } d = \frac{114.2 \text{ g}}{12.8 \text{ mL}} = 8.92 \text{ g/mL}$$

$$\text{glycerin: } d = \frac{63.0 \text{ g}}{50.0 \text{ mL}} = 1.26 \text{ g/mL}$$

$$\text{helium: } d = \frac{0.286 \text{ g}}{1500 \text{ mL}} = 1.91 \times 10^{-4} \text{ g/mL}$$

b. Copper: Doubling the pressure will not influence the volume, mass, or density of a solid.

Glycerin: Doubling the pressure will not significantly influence the volume and will not influence the mass or density of a liquid.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Helium: The increased pressure will cause the volume to decrease. The mass will not be changed, so the density will increase.

6.2 $d = \frac{m}{V}$, so $m = Vd$

$$m = (1200\ \cancel{\text{mL}})(1.18 \times 10^{-3}\ \text{g}/\cancel{\text{mL}})$$
$$= 1.42\ \text{g}$$

6.3 $\text{KE} = \frac{1}{2}mv^2 = \frac{1}{2}(3.00\ \text{g})(10.0\ \text{cm/s})^2 = 1.50 \times 10^2\ \text{g cm}^2/\text{s}^2$

$\text{KE} = \frac{1}{2}mv^2 = \frac{1}{2}(3.00\ \text{g})(20.0\ \text{cm/s})^2 = 6.00 \times 10^2\ \text{g cm}^2/\text{s}^2$

6.4 The factors used come from the information in Table 6.3.

a. $670\ \cancel{\text{torr}} \times \frac{1\ \text{atm}}{760\ \cancel{\text{torr}}} = 0.882\ \text{atm}$

b. $670\ \cancel{\text{torr}} \times \frac{14.7\ \text{psi}}{760\ \cancel{\text{torr}}} = 13.0\ \text{psi}$

6.5 **a.** K = °C + 273 = 27 + 273 = 300 K

b. K = °C + 273 = 0. + 273 = 273 K

c. °C = K − 273 = 0.00 − 273 = − 273°C

d. °C = K − 273 = 100. − 273 = − 173°C

6.6 **a.** Equation 6.8 is used. Temperatures must be converted to kelvins:

$P_i = 1.90$ atm　　$P_f = 1.00$ atm

$V_i = 10.0$ L　　$V_f = ?$

$T_i = 30.°\text{C} = 303$ K　　$T_f = -10.2°\text{C} = 262.8$ K

$$\frac{P_iV_i}{T_i} = \frac{P_fV_f}{T_f}$$

$$\frac{(1.90\ \text{atm})(10.0\ \text{L})}{303\ \text{K}} = \frac{(1.00\ \text{atm})(V_f)}{262.8\ K}$$

Solve for V_f:

$$V_f = \frac{(1.90\ \cancel{\text{atm}})(10.0\ \text{L})(262.8\ \cancel{\text{K}})}{(1.00\ \cancel{\text{atm}})(303\ \cancel{\text{K}})} = 16.5\ \text{L}$$

b. $P_i = 800.$ torr　　$P_f = 900.$ torr

$V_i = 5.00 \times 10^2$ mL　　$V_f = 250.$ mL

$T_i = 300.$ K　　$T_f = ?$

$$\frac{P_iV_i}{T_i} = \frac{P_fV_f}{T_f}$$

$$\frac{(800.\ \text{torr})(5.00 \times 10^2\ \text{mL})}{300.\ \text{K}} = \frac{(900.\ \text{torr})(250.\ \text{mL})}{T_f}$$

Invert both sides and solve for T_f:

$$T_f = \frac{(300.\ \text{K})(900.\ \cancel{\text{torr}})(250.\ \cancel{\text{mL}})}{(800.\ \cancel{\text{torr}})(5.00 \times 10^2\ \cancel{\text{mL}})} = 169\ \text{K}$$

$$°\text{C} = \text{K} - 273 = 169\ \text{K} - 273 = -104°\text{C}$$

6.7 To use the ideal gas law, all quantities must have units to match those of R. The only unit that needs to be changed is the temperature:

$$\text{K} = °\text{C} + 273 = 30.°\text{C} + 273 = 303\ \text{K}$$
$$PV = nRT$$

Solve for P:

$$P = \frac{nRT}{V}$$

$$= \frac{(2.15\ \cancel{\text{mol}})\left(0.0821\ \frac{\cancel{\text{L}}\ \text{atm}}{\cancel{\text{mol}}\ \cancel{\text{K}}}\right)(303\ \cancel{\text{K}})}{(12.6\ \cancel{\text{L}})}$$

$$= 4.24\ \text{atm}$$

6.8 The ideal gas law in the form $PV = mRT/MW$ is solved for MW:

$$\text{MW} = \frac{mRT}{PV}$$

The temperature must be converted to kelvins:

$$\text{K} = 27°\text{C} + 273 = 300\ \text{K}$$

$$\text{MW} = \frac{(3.35\ \text{g})\left(0.0821\ \frac{\cancel{\text{L}}\ \cancel{\text{atm}}}{\text{mol}\ \cancel{\text{K}}}\right)(300\ \cancel{\text{K}})}{(1.21\ \cancel{\text{atm}})(2.00\ \cancel{\text{L}})}$$

$$= 34.1\ \text{g/mol}$$

This matches the molecular weight of H_2S.

6.9 $P_{\text{total}} = P_{\text{He}} + P_{N_2} + P_{O_2}$

The partial pressures of N_2 and O_2 are changed to torr before adding. The factors used come from information in Table 6.3.

P_{N_2}: $0.200\ \cancel{\text{atm}} \times \frac{760\ \text{torr}}{1\ \cancel{\text{atm}}} = 152\ \text{torr}$

P_{O_2}: $7.35\ \cancel{\text{psi}} \times \frac{760\ \text{torr}}{14.7\ \cancel{\text{psi}}} = 380\ \text{torr}$

$P_{\text{total}} = P_{\text{He}} + P_{N_2} + P_{O_2} = 310\ \text{torr} + 152\ \text{torr} + 380\ \text{torr} = 842\ \text{torr}$

6.10 The lighter (least massive) helium molecules will diffuse faster than the neon molecules. The relationship between the diffusion rates is given by Graham's law.

$$\frac{\text{Rate of He}}{\text{Rate of Ne}} = \sqrt{\frac{\text{mass of Ne}}{\text{mass of He}}} = \sqrt{\frac{20.18}{4.003}}$$
$$= \sqrt{5.041} = 2.25$$

Thus, rate of He = 2.25 rate of Ne. So, helium is seen to diffuse at a rate more than twice that of neon.

6.11 **a.** Evaporation is endothermic.

b. Freezing is exothermic.

c. Melting is endothermic.

6.12 The lower the forces between particles, the higher will be the vapor pressure.

a. Both substances form hydrogen bonds, but dispersion forces are stronger in propyl alcohol. Thus, methyl alcohol has the higher vapor pressure.

b. The only forces acting between the molecules in each case are dispersion forces. These are stronger between the heavier nitrogen molecules, so helium has the higher vapor pressure.

c. Molecules of HF form strong hydrogen bonds with one another, whereas the only forces between neon molecules are weak dispersion forces. Thus, neon has the higher vapor pressure.

6.13 Heat absorbed = (mass)(specific heat)(temp. change). The specific heat of helium is obtained from Table 6.8.

$$\begin{aligned}\text{Heat absorbed} &= (1000\text{ g})(1.25\text{ cal/g °C})(700\text{°C} - 25\text{°C})\\ &= 8.44 \times 10^5\text{ cal}\end{aligned}$$

6.14 Heat absorbed = (mass)(heat of vaporization). The heat of vaporization for water was given in the text.

$$\text{Heat absorbed} = (5000\text{ g})(540\text{ cal/g}) = 2.70 \times 10^6\text{ cal}$$

Chapter 7

7.1 **a.** Solvent is gold; solutes are copper, zinc, and nickel.

b. Solvent is nitrogen; solutes are oxygen, argon, and the other gases.

7.2 At 80°C, a saturated solution of KNO_3 contains about 181 g of solute/100 g of H_2O, and a saturated solution of NaBr contains about 118 g of solute per 100 g H_2O. At 50°C both solutions are still saturated, but the KNO_3 solution contains only about 102 g of solute per 100 g H_2O, while the NaBr solution contains about 117 g of solute per 100 g H_2O. Thus, the solubility of KNO_3 is seen to be much more temperature dependent than the solubility of NaBr.

7.3 **a.** The solubility of nitrates and lack of solubility of sulfates and carbonates of barium makes barium nitrate, $Ba(NO_3)_2$, the salt to use. More of it would dissolve and would release more Ba^{2+} ions.

b. Like dissolves like, so oil will dissolve best in oily solvents such as light mineral oil or gasoline. Light mineral oil is the solvent used because it leaves a residue that is similar to the natural oily secretions found on the bird feathers. Gasoline would be hazardous to use (flammable) and leaves no such useful residue.

7.4 **a.** The data may be substituted directly into Equation 7.5:

$$M = \frac{1.25\text{ mol solute}}{2.50\text{ L solution}} = 0.500\,\frac{\text{mol solute}}{\text{L solution}}$$

The solution is 0.500 molar, or 0.500 M.

b. In this problem, the volume of solution must be converted to liters before the data are substituted into Equation 7.5:

$$(225\ \cancel{\text{mL}}\text{ solution})\left(\frac{1\text{ L}}{1000\ \cancel{\text{mL}}}\right) = 0.225\text{ L solution}$$

$$M = \frac{0.486\text{ mol solute}}{0.225\text{ L solution}} = 2.16\,\frac{\text{mol solute}}{\text{L solution}}$$

The solution is 2.16 molar, or 2.16 M.

c. In this problem, the volume of solution must be converted to liters and the mass of solute must be converted to moles before the data can be substituted into Equation 7.5:

$$(100\ \cancel{\text{mL}}\text{ solution})\left(\frac{1\text{ L}}{1000\ \cancel{\text{mL}}}\right) = 0.100\text{ L solution}$$

$$(2.60\ \cancel{\text{g NaCl}})\left(\frac{1\text{ mol NaCl}}{58.44\ \cancel{\text{g NaCl}}}\right) = 0.0445\text{ mol NaCl}$$

In the last calculation, the factor $\frac{1\text{ mol NaCl}}{58.44\text{ g NaCl}}$ comes from the calculated formula weight of 58.44 u for NaCl. The data are now substituted into Equation 7.5:

$$M = \frac{0.0445\text{ mol NaCl}}{0.100\text{ L solution}} = 0.445\,\frac{\text{mol NaCl}}{\text{L solution}}$$

The solution is 0.445 molar, or 0.445 M.

7.5 **a.** To calculate %(w/w), the mass of solute contained in a specific mass of solution is needed. The mass of solute is 0.900 g, and the mass of solution is equal to the solvent mass (100 g) plus the solute mass (0.900 g):

$$\%(\text{w/w}) = \frac{\text{solute mass}}{\text{solution mass}} \times 100 = \frac{0.900\ \cancel{\text{g}}}{100.9\ \cancel{\text{g}}} \times 100 = 0.892\ \%(\text{w/w})$$

To calculate %(w/v), the number of grams of solute must be known along with the number of milliliters of solution. The mass of solute is 0.900 g, and the solution volume is 100 mL:

$$\%(\text{w/v}) = \frac{\text{g of solute}}{\text{mL of solution}} \times 100 = \frac{0.900\text{ g}}{100\text{ mL}} \times 100 = 0.900\ \%(\text{w/v})$$

b. The given quantity is 30 mL of beverage, and the desired quantity is milliliters of pure alcohol. The %(v/v) provides the necessary factor:

$$30\ \cancel{\text{mL beverage}} \times \frac{45\text{ mL alcohol}}{100\ \cancel{\text{mL beverage}}} = 14\text{ mL alcohol}$$

7.6 **a.** $M = \dfrac{\text{mol of solute}}{\text{liters of solution}}$

$$\begin{aligned}\text{mol of solute} &= (\text{M})(\text{liters of solution})\\ &= (1.00\text{ M})(0.500\text{ L})\\ &= 0.500\text{ mol of solute}\end{aligned}$$

The solute is $MgCl_2$, which has a formula weight of 95.2 u. The formula weight provides the factor in the following calculation:

$$0.500\ \cancel{\text{mol MgCl}_2} \times \frac{95.2\text{ g MgCl}_2}{1\ \cancel{\text{mol MgCl}_2}} = 47.6\text{ g MgCl}_2$$

The solution is prepared by putting 47.6 g of $MgCl_2$ into a 500-mL flask and adding pure water to the mark, making certain all the solid solute dissolves and the resulting solution is well mixed.

b.

$$\begin{aligned}\%(\text{w/v}) &= \frac{\text{g of solute}}{\text{mL of solution}} \times 100\\ \text{g of solute} &= \frac{\%(\text{w/v})(\text{mL of solution})}{100}\\ &= \frac{(12.0\%)(100\text{ mL})}{100} = 12.0\text{ g}\end{aligned}$$

The solution is prepared by putting 12.0 g of $MgCl_2$ into a 100-mL flask and adding pure water to the mark, making certain all the solid solute dissolves and the resulting solution is well mixed.

c.

$$\begin{aligned}\%(\text{v/v}) &= \frac{\text{solute volume}}{\text{solution volume}} \times 100\\ \text{solute volume} &= \frac{\%(\text{v/v})(\text{solution volume})}{100}\\ &= \frac{(20.0\%)(1.00\text{ L})}{100} = 0.200\text{ L}\\ &= 200\text{ mL}\end{aligned}$$

The solution is prepared by putting 200 mL of ethylene glycol into a 1.00-L flask and adding pure water to the mark, making certain the two liquids are completely mixed to form the final solution.

7.7 Equation 7.9 is used to calculate the volume of 6.00 M NaOH solution needed.

$$(C_c)(V_c) = (C_d)(V_d)$$

$$(6.00\text{ M})(V_c) = (0.250\text{ M})(500\text{ mL})$$

$$V_c = \frac{(0.250\ \cancel{\text{M}})(500\text{ mL})}{(6.00\ \cancel{\text{M}})} = 20.8\text{ mL}$$

The solution is prepared by putting 20.8 mL of 6.00 M NaOH solution into a 500-mL flask, adding pure water to the mark, and making certain the resulting solution is well mixed.

7.8 **a.** Because $CaCl_2$ is a strong electrolyte, it dissociates completely:

$$CaCl_2 \rightarrow Ca^{2+} + 2Cl^-.\ \text{Thus, } n = 3.$$

$$\Delta T_b = nK_b\text{M} = (3)(0.52°\text{C}/\cancel{\text{M}})(0.100\ \cancel{\text{M}}) = 0.16°\text{C}$$

Because the boiling point of a solution is higher than the boiling point of the pure solvent, ΔT_b is added to the boiling point of the pure solvent.

$$\text{Solution B.P.} = 100.00°\text{C} + 0.16°\text{C} = 100.16°\text{C}$$

$$\Delta T_f = nK_f\text{M} = (3)(1.86°\text{C}/\cancel{\text{M}})(0.100\ \cancel{\text{M}}) = 0.558°\text{C}$$

Because the freezing point of a solution is lower than the freezing point of the pure solvent, ΔT_f is subtracted from the freezing point of the solvent.

$$\text{Solution F.P.} = 0.00°\text{C} - 0.558°\text{C} = -0.558°\text{C} = -0.56°\text{C}$$

$$\begin{aligned}\pi &= n\text{MRT}\\ &= (3)(0.100\ \cancel{\text{mol}}/\cancel{\text{L}})(62.4\ \cancel{\text{L}}\text{ torr}/\cancel{\text{K}}\ \cancel{\text{mol}})(300\ \cancel{\text{K}})\\ &= 5.62 \times 10^3\text{ torr} = 7.39\text{ atm}\end{aligned}$$

b. Because ethylene glycol does not dissociate in solution, $n = 1$.

$$\Delta T_b = nK_b\text{M} = (1)(0.52°\text{C}/\cancel{\text{M}})(0.100\ \cancel{\text{M}}) = 0.052°\text{C}$$

$$\text{Solution B.P.} = 100.00°\text{C} + 0.052°\text{C} = 100.05°\text{C}$$

$$\Delta T_f = nK_f\text{M} = (1)(1.86°\text{C}/\cancel{\text{M}})(0.100\ \cancel{\text{M}}) = 0.186°\text{C}$$

$$\begin{aligned}\text{Solution F.P.} = 0.00°\text{C} - 0.186°\text{C} &= -0.186°\text{C}\\ &= -0.19°\text{C}\end{aligned}$$

$$\begin{aligned}\pi &= nMRT\\ &= (1)(0.100\ \cancel{\text{mol}}/\cancel{\text{L}})(62.4\ \cancel{\text{L}}\text{ torr}/\cancel{\text{K}}\ \cancel{\text{mol}})(300\ \cancel{\text{K}})\\ &= 1.87 \times 10^3\text{ torr} = 2.46\text{ atm}\end{aligned}$$

Chapter 8

8.1 Because only Ce^{4+} and Fe^{2+} are mixed, the initial concentration of Ce^{3+} is 0.

$$\text{Rate} = \frac{C_t - C_0}{\Delta t} = \frac{1.50 \times 10^{-5}\text{ mol/L} - 0\text{ mol/L}}{75.0\text{ s}}$$

$$= 2.00 \times 10^{-7}\,\frac{\text{mol/L}}{\text{s}}$$

8.2 **a.** $K = \dfrac{[NO_2]^2}{[N_2O_4]}$

b. $K = \dfrac{[N_2O][NO_2]}{[NO]^3}$

8.3 **a.**
$$\begin{aligned}K &= \frac{[IBr]^2}{[Br_2][I_2]}\\ &= \frac{(1.96 \times 10^{-2})^2}{(1.50 \times 10^{-1})(5.00 \times 10^{-2})}\\ &= 5.12 \times 10^{-2}\end{aligned}$$

The small value of K indicates the equilibrium position is toward the left.

b.
$$\begin{aligned}K &= \frac{[NH_3]^2}{[N_2][H_2]^3}\\ &= \frac{(9.00)^2}{(9.23 \times 10^{-3})(2.77 \times 10^{-2})^3}\\ &= 4.13 \times 10^8\end{aligned}$$

The large K value indicates the equilibrium position is toward the right.

8.4 **a.** $\text{Heat} + NH_4NO_3(s) \rightleftarrows NH_4^+(aq) + NO_3^-(aq)$

The equilibrium will shift to the right when heat is added in an attempt to use up the added heat. This shift corresponds to dissolving more of the solid at the higher temperature. The solubility is higher at a higher temperature.

b. $2SO_2(g) + O_2(g) \rightleftarrows 2SO_3(g)$

If O_2 were removed from an equilibrium mixture, the equilibrium would shift left in an attempt to replenish the removed O_2. This shift would reduce the amount of SO_3 present at equilibrium, which means the concentration of SO_3 would be lower than it was in the initial equilibrium.

Chapter 9

9.1 **a.**
$$\underset{\text{acid}}{HC_2H_3O_2} + \underset{\text{base}}{H_2O} \rightleftarrows \underset{\text{acid}}{H_3O^+} + \underset{\text{base}}{C_2H_3O_2^-}$$

conjugate pair

conjugate pair

b.
$$\underset{\text{base}}{NO_2^-} + \underset{\text{acid}}{H_2O} \rightleftarrows \underset{\text{base}}{OH^-} + \underset{\text{acid}}{HNO_2}$$

conjugate pair

conjugate pair

c.
$$\underset{\text{acid}}{HS^-} + \underset{\text{base}}{H_2O} \rightleftarrows \underset{\text{acid}}{H_3O^+} + \underset{\text{base}}{S^{2-}}$$

conjugate pair

conjugate pair

9.2 **a.** The anhydrous compound is called hydrogen iodide. The name of the water solution is obtained by dropping *hydrogen* from the anhydrous compound name and adding the prefix *hydro-* to the stem *iod*. The *-ide* suffix on the *iod* stem is replaced by the suffix *-ic* to give the name *hydroiodic*. The word *acid* is added, giving the final name *hydroiodic acid* for the water solution.

b. The anhydrous compound is called hydrogen bromide. The name of the water solution is obtained the same way it was for HI(aq) in part a, using the stem *brom* in place of *iod*. The resulting name for the water solution is *hydrobromic acid.*

9.3 The removal of the two H^+ ions leaves behind the CO_3^{2-} polyatomic ion. From Table 4.6, this ion is the carbonate ion. According to Rules 1–4, the *-ate* suffix is replaced by the *-ic* suffix to give the name *carbonic acid.*

9.4 **a.** If $[\text{OH}^-] = 1 \times 10^{-5}$ mol/L, then $[\text{H}_3\text{O}^+] = 1 \times 10^{-9}$ mol/L

1×10^{-5} is a larger number than 1×10^{-9}, so the solution is basic.

b. $[\text{H}_3\text{O}^+] = 1 \times 10^{-5}$ mol/L, then $[\text{OH}^-] = 1 \times 10^{-9}$ mol/L

1×10^{-5} is the larger number, so the solution is acidic.

9.5 **a.** $\text{pH} = 6$

b. If $[\text{OH}^-] = 1 \times 10^{-3}$ mol/L, then $[\text{H}_3\text{O}^+] = 1 \times 10^{-11}$ mol/L and $\text{pH} = 11$.

9.6 **a.** If $\text{pH} = 1.0$, then $[\text{H}_3\text{O}^+] = 1 \times 10^{-1}$ mol/L and $[\text{OH}^-] = 1 \times 10^{-13}$ mol/L.

b. If $\text{pH} = 10.0$, then $[\text{H}_3\text{O}^+] = 1 \times 10^{-10}$ mol/L and $[\text{OH}^-] = 1 \times 10^{-4}$ mol/L.

9.7 Looking at Table 9.2 as a guide for using your calculator, enter 4.0 and 10^{-8}. Completing the calculation gives $\text{pH} = 7.4$.

9.8 Looking at Table 9.3 as a guide for using your calculator, enter 7.20. Completing the calculation gives $[\text{H}_3\text{O}^+] = 6.3 \times 10^{-8}$.

9.9 According to Table 9.4, concentrated NH_3 stock solution is 15 M. Equation 7.9 is used to determine the amount of this solution needed.

$$C_cV_c = C_dV_d$$
$$(15\text{ M})(V_c) = (3.0\text{ M})(500\text{ mL})$$
$$V_c = \frac{(3.0\ \cancel{\text{M}})(500\text{ mL})}{(15\ \cancel{\text{M}})}$$
$$= 100\text{ mL}$$

Because the resulting solution molarity is given using only two significant figures, the volumes can be measured using graduated cylinders. Measure 100 mL of stock (15 M) aqueous ammonia, put it into a container and add 400 mL of distilled water. Mix the resulting solution well.

9.10 $2\text{HCl}(aq) + \text{Sr}(\text{HCO}_3)_2(s) \rightarrow \text{SrCl}_2(aq) + 2\text{CO}_2(g) + 2\text{H}_2\text{O}(\ell)$

Total Ionic: $2\text{H}^+(aq) + 2\text{Cl}^-(aq) + \text{Sr}(\text{HCO}_3)_2(s) \rightarrow \text{Sr}^{2+}(aq) + 2\text{Cl}^-(aq) + 2\text{CO}_2(g) + 2\text{H}_2\text{O}(\ell)$

Cl^- is a spectator ion.

Net Ionic: $2\text{H}^+(aq) + \text{Sr}(\text{HCO}_3)_2(s) \rightarrow \text{Sr}^{2+}(aq) + 2\text{CO}_2(g) + 2\text{H}_2\text{O}(\ell)$

9.11 **a.** Molecular: $\text{Ca}(s) + 2\text{H}_2\text{O}(\ell) \rightarrow \text{H}_2(g) + \text{Ca}(\text{OH})_2(s)$

Total Ionic: $\text{Ca}(s) + 2\text{H}_2\text{O}(\ell) \rightarrow \text{H}_2(g) + \text{Ca}(\text{OH})_2(s)$

Net Ionic: $\text{Ca}(s) + 2\text{H}_2\text{O}(\ell) \rightarrow \text{H}_2(g) + \text{Ca}(\text{OH})_2(s)$

All three equations are the same because none of the reactants or products form ions in solution.

b. Molecular: $\text{Mg}(s) + \text{H}_2\text{SO}_4(aq) \rightarrow \text{H}_2(g) + \text{MgSO}_4(aq)$

Total Ionic: $\text{Mg}(s) + 2\text{H}^+(aq) + \text{SO}_4^{\ 2-}(aq) \rightarrow \text{H}_2(g) + \text{Mg}^{2+}(aq) + \text{SO}_4^{\ 2-}(aq)$

The $\text{SO}_4^{\ 2-}$ is a spectator ion.

Net Ionic: $\text{Mg}(s) + 2\text{H}^+(aq) \rightarrow \text{H}_2(g) + \text{Mg}^{2+}(aq)$

9.12 **a.** Molecular: $\text{HNO}_3(aq) + \text{NaOH}(aq) \rightarrow \text{H}_2\text{O}(\ell) + \text{NaNO}_3(aq)$

Total Ionic: $\text{H}^+(aq) + \text{NO}_3^{\ -}(aq) + \text{Na}^+(aq) + \text{OH}^-(aq) \rightarrow \text{H}_2\text{O}(\ell) + \text{Na}^+(aq) + \text{NO}_3^{\ -}(aq)$

Na^+ and $\text{NO}_3^{\ -}$ are spectator ions.

Net Ionic: $\text{H}^+(aq) + \text{OH}^-(aq) \rightarrow \text{H}_2\text{O}(\ell)$

b. Molecular: $\text{H}_2\text{SO}_4(aq) + 2\text{KOH}(aq) \rightarrow 2\text{H}_2\text{O}(\ell) + \text{K}_2\text{SO}_4(aq)$

Total Ionic:
$2\text{H}^+(aq) + \text{SO}_4^{\ 2-}(aq) + 2\text{K}^+(aq) + 2\text{OH}^-(aq) \rightarrow 2\text{H}_2\text{O}(\ell) + 2\text{K}^+(aq) + \text{SO}_4^{\ 2-}(aq)$

K^+ and $\text{SO}_4^{\ 2-}$ are spectator ions.

Net Ionic: $2\text{H}^+(aq) + 2\text{OH}^-(aq) \rightarrow 2\text{H}_2\text{O}(\ell)$

9.13 $6\text{HCl}(aq) + 2\text{Al}(s) \rightarrow 2\text{AlCl}_3(aq) + 3\text{H}_2(g)$

$6\text{HCl}(aq) + \text{Al}_2\text{O}_3(s) \rightarrow 2\text{AlCl}_3(aq) + 3\text{H}_2\text{O}(\ell)$

$3\text{HCl}(aq) + \text{Al}(\text{OH})_3(s) \rightarrow \text{AlCl}_3(aq) + 3\text{H}_2\text{O}(\ell)$

$6\text{HCl}(aq) + \text{Al}_2(\text{CO}_3)_3(s) \rightarrow 2\text{AlCl}_3(aq) + 3\text{H}_2\text{O}(\ell) + 3\text{CO}_2(g)$

$3\text{HCl}(aq) + \text{Al}(\text{HCO}_3)_3(s) \rightarrow \text{AlCl}_3(aq) + 3\text{H}_2\text{O}(\ell) + 3\text{CO}_2(g)$

9.14 **a.** The dissociation reaction is $\text{NaCl}(aq) \rightarrow \text{Na}^+(aq) + \text{Cl}^-(aq)$. Thus, 1 mol of NaCl produces 1 mol of Na^+ or 1 mol of positive charges. Thus, 1 mol NaCl = 1 eq NaCl. Therefore,

$$0.10\ \cancel{\text{mol NaCl}} \times \frac{1\text{ eq NaCl}}{1\ \cancel{\text{mol NaCl}}} = 0.10\text{ eq NaCl}$$

Also, because 1 eq = 1000 meq,

$$0.10\ \cancel{\text{eq}} \times \frac{1000\text{ meq}}{1\ \cancel{\text{eq}}} = 1.0 \times 10^2\text{ meq}$$

b. The dissociation reaction is $\text{Mg}(\text{NO}_3)_2(aq) \rightarrow \text{Mg}^{2+}(aq) + 2\text{NO}_3^{\ -}(aq)$. Thus, 1 mol of $\text{Mg}(\text{NO}_3)_2$ produces 1 mol of Mg^{2+} or 2 mol of positive charges. Thus, 1 mol $\text{Mg}(\text{NO}_3)_2$ = 2 eq $\text{Mg}(\text{NO}_3)_2$. Therefore,

$$0.10\ \cancel{\text{mol Mg}(\text{NO}_3)_2} \times \frac{2\text{ eq Mg}(\text{NO}_3)_2}{1\ \cancel{\text{mol Mg}(\text{NO}_3)_2}}$$
$$= 0.20\text{ eq Mg}(\text{NO}_3)_2$$

Also, because 1 eq = 1000 meq,

$$0.20\ \cancel{\text{eq}} \times \frac{1000\text{ meq}}{1\ \cancel{\text{eq}}} = 2.0 \times 10^2\text{ meq}$$

9.15 The Cl^- ion has a single charge, so we may write:

1.00 mol NaCl = 1.00 mol Cl^- = 1.00 eq Cl^- = 1.00 eq NaCl

As in Example 9.11, the pattern for the calculation is liters solution $A \rightarrow$ eq A, and the pathway is liters Cl^- solution $\rightarrow$ eq Cl^-. The conversion factor comes from the concentration of 0.103 eq/L given in the problem:

$$(0.250\ \cancel{\text{L}}\ \text{Cl}^-\ \cancel{\text{solution}})\left(\frac{0.103\text{ eq Cl}^-}{1.00\ \cancel{\text{L}}\ \cancel{\text{solution}}}\right) = 0.0258\text{ eq Cl}^-$$

The equivalents of Cl^- are converted to the quantities asked for by using factors from the relationships given above and the formula weight for NaCl, 58.44 u:

$$(0.0258\ \cancel{\text{eq Cl}^-})\left(\frac{1.00\text{ eq NaCl}}{1.00\ \cancel{\text{eq Cl}^-}}\right) = 0.0258\text{ eq NaCl}$$

$$(0.0258\ \cancel{\text{eq NaCl}})\left(\frac{1.00\ \text{mol NaCl}}{1.00\ \cancel{\text{eq NaCl}}}\right) = 0.0258\ \text{mol NaCl}$$

$$(0.0258\ \cancel{\text{mol NaCl}})\left(\frac{58.44\ \text{g NaCl}}{1.00\ \cancel{\text{mol NaCl}}}\right) = 1.51\ \text{g NaCl}$$

9.16 **a.** $HPO_4^{2-} \rightleftarrows H^+ + PO_4^{3-}$

$$K_a = \frac{[H^+][PO_4^{3\,-}]}{[HPO_4^{2\,-}]}$$

b. $HNO_2 \rightleftarrows H^+ + NO_2^-$

$$K_a = \frac{[H^+][NO_2^-]}{[HNO_2]}$$

c. $HF \rightleftarrows H^+ + F^-$

$$K_a = \frac{[H^+][F^-]}{[HF]}$$

9.17 **a.** In a series of similar oxyacids, acid strength increases with increases in the number of oxygens: $HClO_3$, $HClO_2$, $HClO$.

b. The anion from the weakest acid will be the strongest base. HNO_3 is a stronger acid than HNO_2, so NO_2^- is a stronger base than NO_3^-.

c. The anion of an acid behaves as a weaker acid than the acid from which it came. The anion actually behaves as a base in this case, so $HC_2H_3O_2$ is a stronger acid than $C_2H_3O_2^-$.

9.18 The pattern is liters solution $A \rightarrow$ mol B, and the pathway is liters NaOH solution → mol NaOH → mol H_3PO_4. In combined form, the steps in the factor-unit method are:

Step 1. 0.0141 L NaOH solution

Step 2. 0.0141 L NaOH solution = mol H_3PO_4

Step 3. $$0.0141\ \cancel{\text{L NaOH solution}} \times \frac{0.250\ \cancel{\text{mol NaOH}}}{1\ \cancel{\text{L NaOH solution}}} \times \frac{1\ \text{mol}\ H_3PO_4}{3\ \cancel{\text{mol NaOH}}} = \text{mol}\ H_3PO_4$$

Step 4. $$(0.0141)\left(\frac{0.250}{1}\right)\left(\frac{1\ \text{mol}\ H_3PO_4}{3}\right) = 0.00118\ \text{mol}\ H_3PO_4$$

The molarity of the H_3PO_4 solution is calculated:

$$\begin{aligned} M &= \frac{\text{mol}\ H_3PO_4}{\text{L}\ H_3PO_4\ \text{solution}} \\ &= \frac{0.00118\ \text{mol}\ H_3PO_4}{0.0250\ \text{L}\ H_3PO_4\ \text{solution}} \\ &= \frac{0.0472\ \text{mol}\ H_3PO_4}{\text{L}\ H_3PO_4\ \text{solution}} = 0.0472\ \text{M} \end{aligned}$$

9.19 **a.** The ions resulting from dissociation are Na^+ and NO_3^-. Na^+ is the cation of a strong base, and NO_3^- is the anion of a strong acid. Neither ion will hydrolyze significantly in water, so the solution pH will be about 7.

b. The ions resulting from dissociation are Na^+ and NO_2^-. Na^+ is the cation of a strong base and will not hydrolyze significantly. NO_2^- is the anion of a weak acid and will behave as a base in the hydrolysis reaction. The solution will therefore be basic, and the pH will be higher than 7.

c. The ions resulting from dissociation are K^+ and BO_3^{3-}. K^+ is the cation of a strong base and will not hydrolyze significantly. BO_3^{3-} is the anion of a weak acid and will behave as a base in the hydrolysis reaction. The solution will therefore be basic, and the pH will be higher than 7.

9.20 **a.** Because the acid (HCOOH) and conjugate base ($HCOO^-$) concentrations are the same, the pH will equal pK_a for the acid. This is shown by the following calculation:

$$\begin{aligned} \text{pH} &= \text{p}K_a + \log\frac{[B^-]}{[HB]} \\ &= 3.74 + \log\frac{[HCOO^-]}{[HCOOH]} \\ &= 3.74 + \log\frac{0.22\ \text{mol/L}}{0.22\ \text{mol/L}} \\ &= 3.74 + \log 1 \\ &= 3.74 + 0 = 3.74 \end{aligned}$$

b. The acid is H_2SO_3, and the conjugate base is HSO_3^- (produced when the $NaHSO_3$ salt dissociates).

$$\begin{aligned} \text{pH} &= \text{p}K_a + \log\frac{[B^-]}{[HB]} \\ &= 1.82 + \log\frac{(0.10\ \text{mol/L})}{(0.25\ \text{mol/L})} \\ &= 1.82 + \log 0.40 \\ &= 1.82 - 0.40 \\ &= 1.42 \end{aligned}$$

c. The acid is H_2CO_3 and the conjugate base is HCO_3^-. The desired pH is 7.40. Substitution into Equation 9.54 gives:

$$\text{pH} = \text{p}K_a + \log\frac{[HCO_3^-]}{[H_2CO_3]}$$

$$7.40 = 6.37 + \log\frac{[HCO_3^-]}{[H_2CO_3]}$$

$$7.40 - 6.37 = \log\frac{[HCO_3^-]}{[H_2CO_3]}$$

$$1.03 = \log\frac{[HCO_3^-]}{[H_2CO_3]}$$

We now know the log of the desired ratio. Use Step 3 in Table 9.3 to get the antilog of 1.03. The correctly rounded value is 11. Thus, the concentration of HCO_3^- must be 11 times the concentration of H_2CO_3 in the blood to maintain the desired pH.

Chapter 10

10.1 **a.** ${}^{131}_{53}I$ **b.** ${}^{0}_{-1}\beta$ **c.** ${}^{4}_{4}X$ **d.** ${}^{0}_{-4}X$

10.2 ${}^{234}_{90}Th \rightarrow {}^{0}_{-1}\beta + {}^{234}_{91}Pa$

In general: ${}^{A}_{Z}X \rightarrow {}^{0}_{-1}\beta + {}^{A}_{Z+1}Y$

When a β particle is emitted, the daughter has the same mass number and an atomic number higher by 1 than that of the decaying nucleus.

10.3 ${}^{A}_{Z}X \rightarrow {}^{0}_{1}\beta + {}^{A}_{Z-1}Y$

The atomic number of the daughter is 1 less than that of the decaying nucleus.

10.4 ${}^{A}_{Z}X + {}^{0}_{-1}e \rightarrow {}^{A}_{Z-1}Y$

The atomic number of the daughter is 1 less than that of the decaying nucleus.

10.5 **a.** ${}^{50}_{25}\text{Mn} \rightarrow {}^{0}_{1}\beta + {}^{50}_{24}\text{Cr}$

b. ${}^{54}_{25}\text{Mn} + {}^{0}_{-1}e \rightarrow {}^{54}_{24}\text{Cr}$

c. ${}^{56}_{25}\text{Mn} \rightarrow {}^{0}_{-1}\beta + {}^{56}_{26}\text{Fe}$

d. ${}^{224}_{88}\text{Ra} \rightarrow {}^{4}_{2}\alpha + {}^{220}_{86}\text{Rn}$

10.6 During the first half-life, the original 200.00 mg will be reduced to 100.00 mg. This will be reduced to 50.00 mg during the second half-life and to 25.00 mg during the third. Thus, 3 half-lives or 3(7.7 min) = 23.1 min will be required.

10.7 The elapsed time of 79.8 hours is 6 half-lives (79.8/13.3 = 6). The fraction remaining is 1/2 × 1/2 × 1/2 × 1/2 × 1/2 × 1/2 = 1/64 of the original diagnostic dose.

10.8 Equation 10.2 is used: $\frac{I_x}{I_y} = \frac{d_y^2}{d_x^2}$

$$\frac{10.0\text{ units}}{I_5} = \frac{(5.0\text{ ft})^2}{(25\text{ ft})^2}$$

$$I_5 = \frac{(10.0\text{ units})(25\,\cancel{\text{ft}})^2}{(5.0\,\cancel{\text{ft}})^2} = 250\text{ units}$$

10.9 ${}^{55}_{25}\text{Mn} + {}^{1}_{1}p \rightarrow {}^{1}_{0}n + {}^{55}_{26}\text{Fe}$

The product is iron-55.

Chapter 11

11.1 Look for the presence of carbon atoms.

a. inorganic

b. organic

c. organic

d. inorganic

e. organic

f. inorganic

11.2 Refer to Table 11.1 for help.

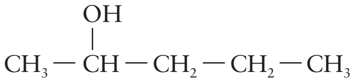
a. organic

b. organic

c. inorganic

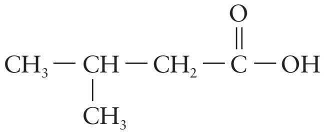
11.3 Compound (a) is a structural isomer because it has the same molecular formula but a different structural formula.

11.4 **a.**



$CH_3-\overset{\overset{OH}{|}}{CH}-CH_2-CH_2-CH_3$

b.



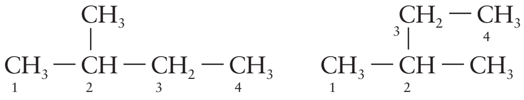
$CH_3-\underset{\underset{CH_3}{|}}{CH}-CH_2-\overset{\overset{O}{\|}}{C}-OH$

11.5 **a.** Normal

b. Branched

11.6 **a.** Same molecule: In both molecules, the five carbons are bonded in a continuous chain.

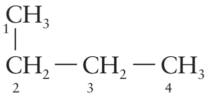
b. Same molecule: In both molecules, there is a continuous chain of four carbons with a branch at position 2.



$\underset{1}{CH_3}-\underset{2}{\overset{\overset{CH_3}{|}}{CH}}-\underset{3}{CH_2}-\underset{4}{CH_3} \qquad \underset{1}{CH_3}-\underset{2}{\overset{\overset{\overset{3}{CH_2}-\overset{4}{CH_3}}{|}}{CH}}-CH_3$

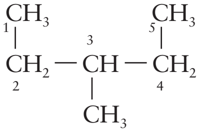
c. Structural isomers: Both molecules have a continuous chain of five carbons, but the branch is located at different positions.

11.7 **a.**



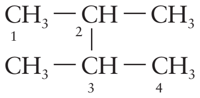
$\underset{2}{\overset{\overset{1\,CH_3}{|}}{CH_2}}-\underset{3}{CH_2}-\underset{4}{CH_3}$ a butane

b.



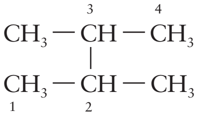
$\underset{2}{\overset{\overset{1\,CH_3}{|}}{CH_2}}-\overset{3}{\underset{\underset{CH_3}{|}}{CH}}-\underset{4}{\overset{\overset{5\,CH_3}{|}}{CH_2}}$ a pentane

c.



$$\begin{array}{c} \underset{1}{CH_3}-\overset{}{\underset{}{CH}}{}^{2}-CH_3 \\ | \\ CH_3-\underset{3}{CH}-\underset{4}{CH_3} \end{array}$$

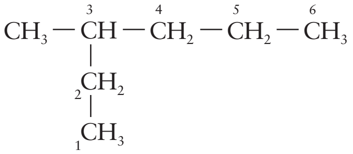
or



$$\begin{array}{c} CH_3-\overset{3}{CH}-\overset{4}{CH_3} \\ | \\ \underset{1}{CH_3}-\underset{2}{CH}-CH_3 \end{array}$$

a butane

11.8 **a.**



$CH_3-\overset{3}{\underset{\underset{\underset{\underset{1\,CH_3}{|}}{2\,CH_2}}{|}}{CH}}-\overset{4}{CH_2}-\overset{5}{CH_2}-\overset{6}{CH_3}$

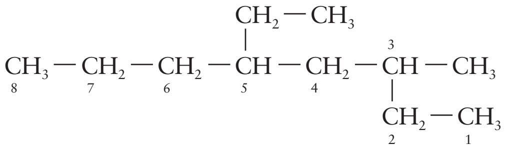
A CH_3 group is located at position 3. If the chain had been numbered beginning at the right, the CH_3 group would have been at position 4.

b. Numbering from the left, groups are located at positions 5, 5, 7. From the right, the groups are at positions 2, 4, 4. The first difference occurs with the first number, so numbering from the right (2, 4, 4) is correct.

11.9 Proceeding from the left, the groups are methyl, propyl, isopropyl, *sec*-butyl, and ethyl.

11.10 **a.** The chain is numbered from the right to give 2-methylhexane.

b.



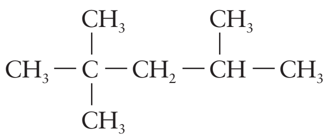
$\underset{8}{CH_3}-\underset{7}{CH_2}-\underset{6}{CH_2}-\underset{5}{\overset{\overset{CH_2-CH_3}{|}}{CH}}-\underset{4}{CH_2}-\overset{3}{\underset{\underset{\underset{2}{CH_2}-\underset{1}{CH_3}}{|}}{CH}}-CH_3$

The chain is numbered from the right to give 5-ethyl-3-methyloctane.

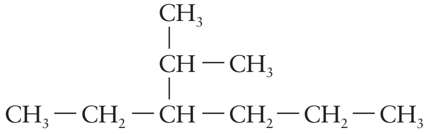
c. The chain is numbered from the right to give 4-isopropyl-2, 3-dimethylheptane.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

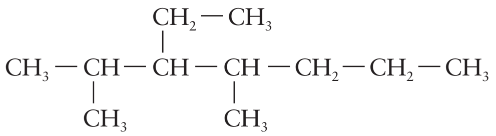
11.11

a. 

$$\mathrm{CH_3-\overset{\overset{CH_3}{|}}{\underset{\underset{CH_3}{|}}{C}}-CH_2-\overset{\overset{CH_3}{|}}{CH}-CH_3}$$

b. 

$$\mathrm{CH_3-CH_2-\overset{\overset{\overset{CH_3}{|}}{CH-CH_3}}{\overset{|}{CH}}-CH_2-CH_2-CH_3}$$

c. 

$$\mathrm{CH_3-\underset{\underset{CH_3}{|}}{CH}-\overset{\overset{CH_2-CH_3}{|}}{CH}-\underset{\underset{CH_3}{|}}{CH}-CH_2-CH_2-CH_3}$$

11.12 **a.** 1,4-dimethylcyclohexane

b. The correct name is ethylcyclopropane. When only one group is attached to a ring, the position is not designated.

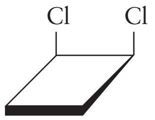
c. The name 1-ethyl-2-methylcyclopentane is correct, whereas 2-ethyl-1-methylcyclopentane is incorrect because the ring numbering begins with the carbon attached to the first group alphabetically.

11.13 **a.** (1) *Trans* because the two Br's are on opposite sides of the ring.

(2) *Cis*; both Cl's are on the same side.

(3) *Cis*; the two groups are on the same side.

b. In showing geometric isomers of ring compounds, it helps to draw the ring in perspective:



11.14 **a.** $2\ C_5H_{12} + 11\ O_2 \longrightarrow 10\ CO + 12\ H_2O$

pentane

b. $2\ C_6H_{14} + 19\ O_2 \longrightarrow 12\ CO_2 + 14\ H_2O$

hexane

Chapter 12

12.1 In each of these alkenes, the double-bonded carbons occur at positions 1 and 2.

a. 3-bromo-1-propene

b. 2-ethyl-1-pentene

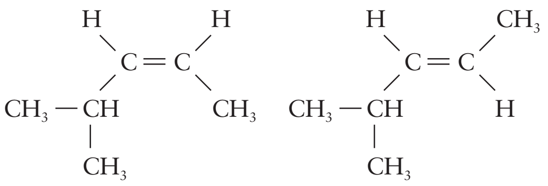
c. 3,4-dimethylcyclohexene

12.2 **a.** The chain is correctly numbered from the right to give 2-methyl-1,3-butadiene.

b. The chain is correctly numbered from the left to give 2-methyl-1,3,6-octatriene.

c. 7-bromo-1,3,5-cycloheptatriene

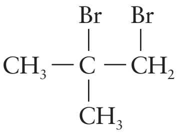
12.3 **a.** This structure does not exhibit *cis-trans* isomerism because there are two H's attached to the carbon at position 1.

b. 

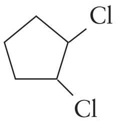
cis *trans*

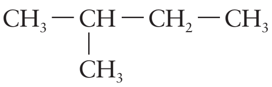
c. This structure does not exhibit *cis-trans* isomerism because there are two methyl groups attached to the left double-bonded carbon.

12.4

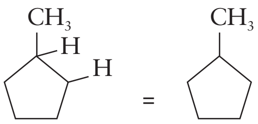
a. 

$$\mathrm{CH_3-\overset{\overset{Br}{|}}{\underset{\underset{CH_3}{|}}{C}}-\overset{\overset{Br}{|}}{CH_2}}$$

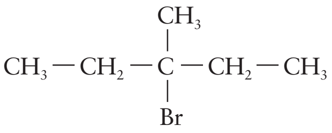
b. 

12.5 **a.** 

$$\mathrm{CH_3-\underset{\underset{CH_3}{|}}{CH}-CH_2-CH_3}$$

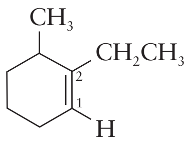
b. 

12.6 **a.** The major product will be the one where H attaches to the CH carbon:

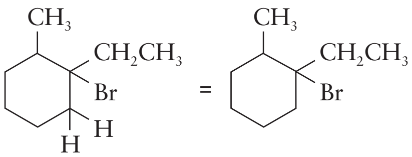


$$\mathrm{CH_3-CH_2-\overset{\overset{CH_3}{|}}{\underset{\underset{Br}{|}}{C}}-CH_2-CH_3}$$

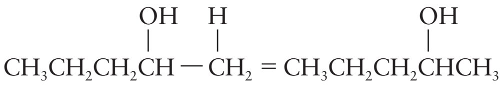
b. Position 1 on the ring has an attached hydrogen, whereas position 2 does not have any attached hydrogens:



Thus, H attaches at position 1 to give:

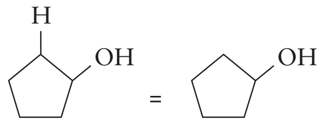


12.7 **a.** Markovnikov's rule predicts that H will attach at position 1 to give:

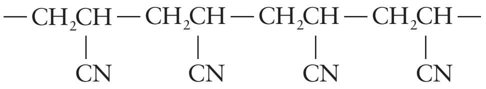


$$\mathrm{CH_3CH_2CH_2\overset{\overset{OH}{|}}{CH}-\overset{\overset{H}{|}}{CH_2} = CH_3CH_2CH_2\overset{\overset{OH}{|}}{C}HCH_3}$$

b.



12.8



$-CH_2\underset{\underset{CN}{|}}{CH}-CH_2\underset{\underset{CN}{|}}{CH}-CH_2\underset{\underset{CN}{|}}{CH}-CH_2\underset{\underset{CN}{|}}{CH}-$

12.9 Each chain is correctly numbered from the right.

a. 2-pentyne **b.** 5-methyl-2-hexyne

12.10 **a.** Numbers or the term *meta* may be used:

1,3-diethylbenzene or *m*-diethylbenzene

b. The compound must be named as a derivative of cyclopentane. The correct name is 1-chloro-3-phenylcyclopentane.

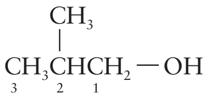
c. Numbers must be used when there are three groups: 1,2,3-tribromobenzene.

d. If the compound is named as a derivative of benzoic acid, then the methyl group is at position 2. The name is 2-methylbenzoic acid.

Chapter 13

13.1

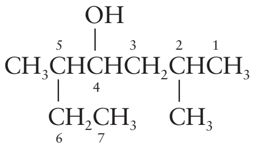
a.



$\underset{3}{CH_3}\underset{2}{\overset{\overset{CH_3}{|}}{CH}}\underset{1}{CH_2}-OH$

2-methyl-1-propanol

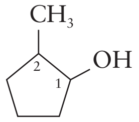
b.



$CH_3\overset{5}{\underset{\underset{\underset{6\quad 7}{CH_2CH_3}}{|}}{CH}}\underset{4}{\overset{\overset{OH}{|}}{CH}}\overset{3}{CH_2}\overset{2}{\underset{\underset{CH_3}{|}}{CH}}\overset{1}{CH_3}$

2,5-dimethyl-4-heptanol

c.



2-methylcyclopentanol

13.2 **a.** 1,4-butanediol **b.** 1,2-cyclohexanediol

13.3 Because the compound is named as a phenol, the OH group is at position 1. The name is 2-ethylphenol or *o*-ethylphenol.

13.4 In each case, count the number of carbon atoms attached to the hydroxy-bearing carbon.

a. primary **b.** secondary **c.** secondary

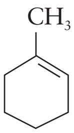
13.5 b, c, a

13.6 Methanol molecules form hydrogen bonds, whereas molecules of propane do not.

13.7 **a.** There are two ways of removing water from this structure, but they both produce the same product:

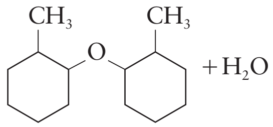
$$CH_3CH{=}CHCH_2CH_3$$

b. Dehydration will occur in the direction that gives the highest number of carbon groups attached to the double-bonded carbons:

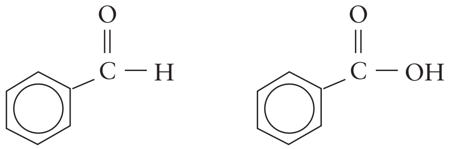


13.8 **a.** $CH_3CH_2CH_2-O-CH_2CH_2CH_3+H_2O$

b.

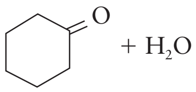


13.9



first product **second product**

13.10



13.11 The alcohols in a and c react because they are secondary and primary, respectively. Alcohol b is tertiary and does not react.

13.12 Working backward, you could prepare an ether product from an alcohol. Thus, the starting alkene must first be converted to an alcohol.

$$CH_2{=}CH_2+H_2O\xrightarrow{H_2SO_4}CH_3CH_2-OH$$

$$2CH_3CH_2-OH\xrightarrow[140^\circ C]{H_2SO_4}CH_3CH_2-O-CH_2CH_3+H_2O$$

13.13 Use Table 13.2 to answer these questions:

a. solvent

b. alcoholic beverages

c. rubbing alcohol

d. antifreeze

e. food moisturizer

f. cough drops

13.14 **a.** antioxidant in gasoline

b. throat lozenges

13.15 **a.** ethyl phenyl ether

b. diisopropyl ether

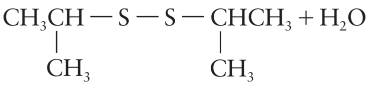
13.16 **a.** 1,2-dimethoxycyclopentane

b. 3-isopropoxypentane

13.17 **a.** Ether molecules do not form hydrogen bonds, whereas alcohol molecules do form hydrogen bonds.

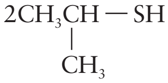
b. They are quite unreactive.

13.18 Oxidation of a thiol produces a disulfide:



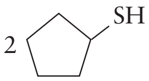
$CH_3\underset{\underset{CH_3}{|}}{CH}-S-S-\underset{\underset{CH_3}{|}}{CH}CH_3+H_2O$

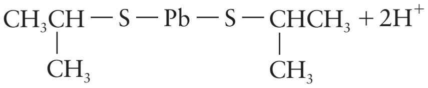
13.19 **a.**



$2CH_3\underset{\underset{CH_3}{|}}{CH}-SH$

b.



13.20 
$\underset{\underset{\displaystyle CH_3}{|}}{CH_3CH} - S - Pb - S - \underset{\underset{\displaystyle CH_3}{|}}{CHCH_3} + 2H^+$

13.21 Ether, phenolic OH, and benzene ring

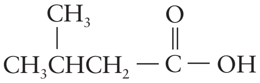
Chapter 14

14.1 **a.** The aldehyde contains five carbon atoms, and the name is pentanal.

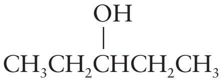
b. The aldehyde carbon is position 1. The name is 3,4-dimethylpentanal.

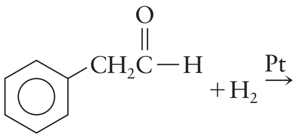
14.2 **a.** The chain is numbered from the right. The name is 4,6-dibromo-2-heptanone.

b. The carbonyl carbon atom is position 1. The name is 2,5-dimethylcyclopentanone.

14.3 **a.** 
$\overset{\displaystyle CH_3}{\overset{|}{CH_3CHCH_2}} - \overset{\displaystyle O}{\overset{\|}{C}} - OH$

b. This is a ketone, and it does not undergo oxidation.

14.4 **a.** 
$CH_3CH_2\overset{\displaystyle OH}{\overset{|}{C}}HCH_2CH_3$

b. 

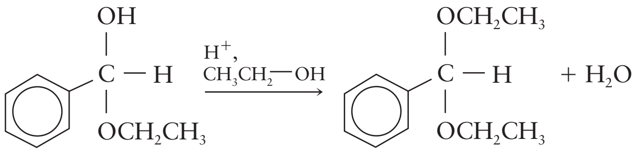
14.5 **a.** Hemiketal

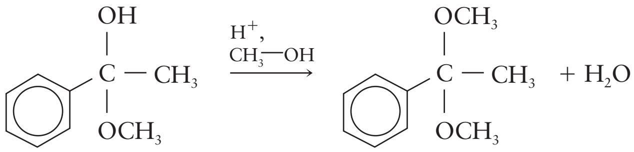
b. None of the above

c. Acetal

d. Hemiacetal

14.6

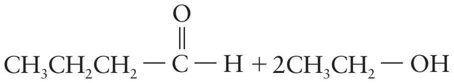
a. 
hemiacetal acetal

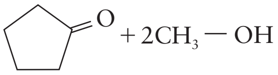
b. 
hemiketal ketal

14.7 **a.** Hemiacetal

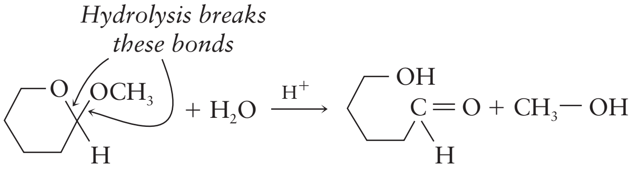
b. Acetal

c. Ketal

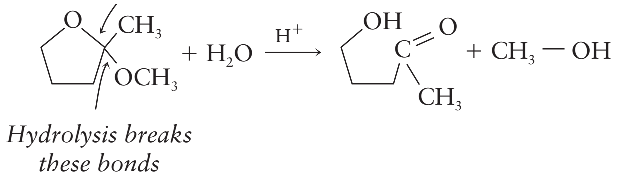
14.8 **a.** 
$CH_3CH_2CH_2 - \overset{\displaystyle O}{\overset{\|}{C}} - H + 2CH_3CH_2 - OH$

b. 

14.9 **a.** This compound is not a hemiacetal or hemiketal because there is no OH group. The presence of the ring hydrogen makes it an acetal.



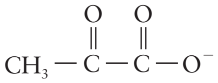
b. An OH group is missing, so this compound is an acetal or ketal. Because the carbon with two attached oxygens does not have a hydrogen present, the compound is a ketal.

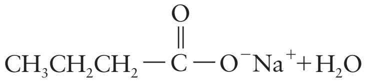


Chapter 15

15.1 **a.** The longest chain beginning with the carboxyl group has four carbon atoms. The name is 2-methylbutanoic acid.

b. The carboxyl group is at position 1. The name is 3,4-dibromobenzoic acid.

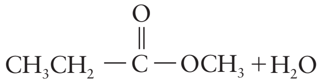
15.2 
$CH_3 - \overset{\displaystyle O}{\overset{\|}{C}} - \overset{\displaystyle O}{\overset{\|}{C}} - O^-$

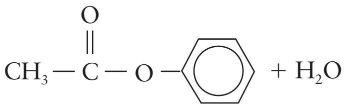
15.3 
$CH_3CH_2CH_2 - \overset{\displaystyle O}{\overset{\|}{C}} - O^-Na^+ + H_2O$

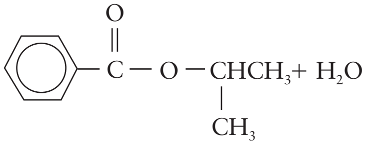
15.4 **a.** This is the lithium salt of 2-methylbenzoic acid. The name is lithium 2-methylbenzoate.

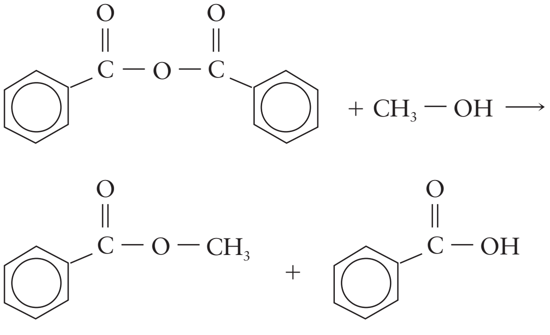
b. This is the sodium salt of butanoic acid. The name is sodium butanoate.

15.5 Each of these reactions requires H^+ as a catalyst. The products are as follows:

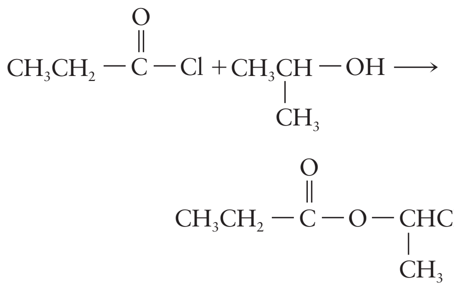
a. 
$CH_3CH_2 - \overset{\displaystyle O}{\overset{\|}{C}} - OCH_3 + H_2O$

b. 

c. 

15.6 **a.** 

b.



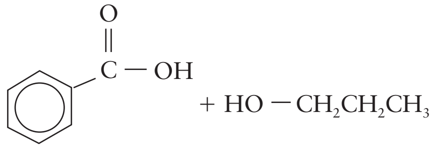
$$CH_3CH_2-\overset{\overset{O}{\|}}{C}-Cl+CH_3\underset{\underset{CH_3}{|}}{CH}-OH\longrightarrow$$

$$CH_3CH_2-\overset{\overset{O}{\|}}{C}-O-\underset{\underset{CH_3}{|}}{CHCH_3}+HCl$$

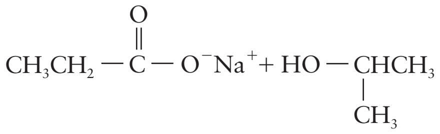
15.7 **a.** The common name for the acid used to prepare this ester is formic acid. The alkyl group attached to oxygen is isopropyl. Thus, the common name is isopropyl formate. The IUPAC name for formic acid is methanoic acid. Thus, the IUPAC name for the ester is isopropyl methanoate.

b. The common and IUPAC names are identical when the carboxylic acid is benzoic acid. The name of the ester is methyl benzoate.

15.8

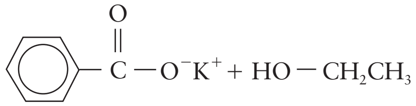


15.9 **a.**



$$CH_3CH_2-\overset{\overset{O}{\|}}{C}-O^-Na^++HO-\underset{\underset{CH_3}{|}}{CHCH_3}$$

b.



Chapter 16

16.1 In each case, count the number of carbon atoms directly attached to the nitrogen.

a. secondary **b.** secondary **c.** tertiary

16.2 **a.** propylamine

b. methylphenylamine

c. ethylpropylamine

16.3 **a.** 1-butanamine

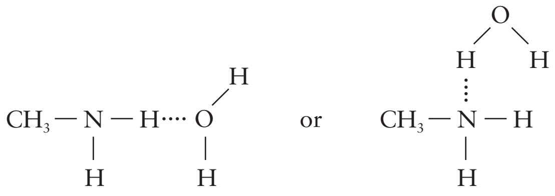
b. *N*-methyl-1-butanamine

16.4 **a.** *N*-ethylaniline

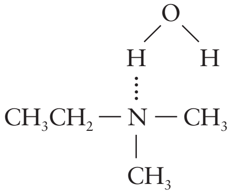
b. *N*-ethyl-*N*-methylaniline

c. 3-ethyl-2-methylaniline

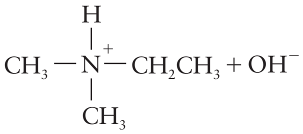
16.5 **a.**



b.

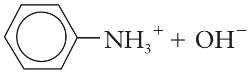


16.6 **a.**

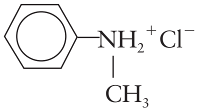


$$CH_3-\overset{\overset{H}{|}}{\underset{\underset{CH_3}{|}}{N^+}}-CH_2CH_3+OH^-$$

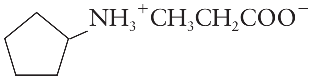
b.



16.7 **a.**

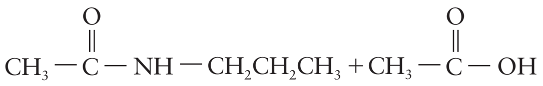


b.



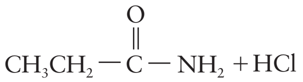
16.8

a.



$$CH_3-\overset{\overset{O}{\|}}{C}-NH-CH_2CH_2CH_3+CH_3-\overset{\overset{O}{\|}}{C}-OH$$

b.



$$CH_3CH_2-\overset{\overset{O}{\|}}{C}-NH_2+HCl$$

16.9 **a.** This amide is derived from butanoic acid. The name is butanamide.

b. hexanamide

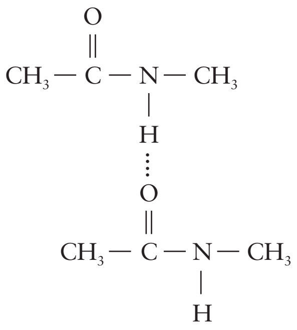
16.10 **a.** This amide is a derivative of the two-carbon acid acetic acid (common name) or ethanoic acid (IUPAC name). The amide is named *N,N*-diethylacetamide (common name) or *N, N*-diethylethanamide (IUPAC name).

b. This amide is a derivative of butyric acid (common name) or butanoic acid (IUPAC name). The amide is named *N*-isobutylbutyramide (common name) or *N*-isobutylbutanamide (IUPAC name).

c. The acid portion of this amide came from benzoic acid. The amide is named *N*-ethyl-*N*-phenylbenzamide.

d. The acid portion of this amide came from 2-methylbenzoic acid. The amide is named 2,*N*-dimethylbenzamide.

16.11 **a.**

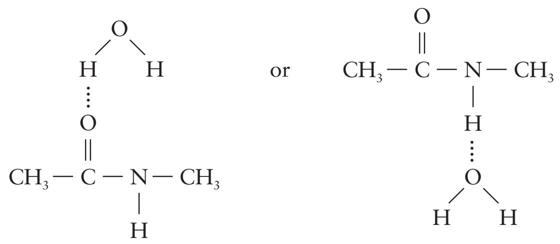


$$CH_3-\overset{\overset{O}{\|}}{C}-\underset{\underset{\underset{\vdots}{H}}{|}}{N}-CH_3$$

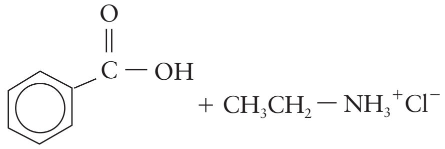
$$CH_3-\overset{\overset{O}{\|}}{C}-\underset{\underset{H}{|}}{N}-CH_3$$

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

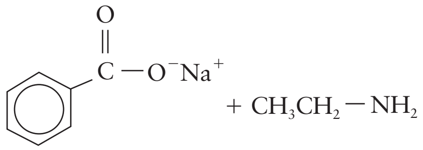
b.



16.12 a. Under acidic conditions, amide hydrolysis produces a carboxylic acid and the salt of an amine.



b. Under basic conditions, amide hydrolysis produces an amine and the salt of a carboxylic acid.



Chapter 17

17.1 In each case, look for the presence of four different groups attached to the colored atom.

a. The carbon is not chiral because of the two attached CH_2OH groups.

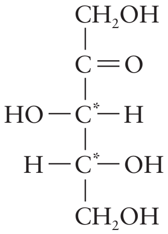
b. Yes

c. The carbon is not chiral because it is attached to two H's.

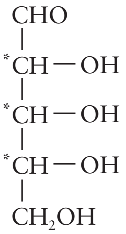
d. Yes

17.2 Each of the atoms marked with an asterisk has four different attached groups and is chiral.

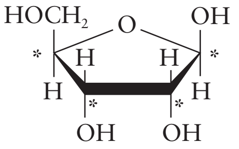
a.



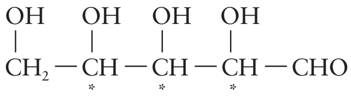
b.



c.

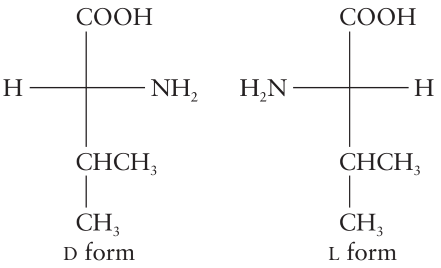


17.3 The chiral carbon atoms (three of them) are marked with an asterisk. Thus, there are 2^3, or 8, possible stereoisomers:



$$\overset{OH}{CH_2}-\underset{*}{\overset{OH}{CH}}-\underset{*}{\overset{OH}{CH}}-\underset{*}{\overset{OH}{CH}}-CHO$$

17.4 The chiral carbon atom is the one with the attached nitrogen. The chiral carbon atom is placed at the intersection of the two lines, and the COOH is placed at the top:



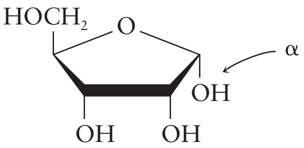
17.5 In each case, look at the direction of the OH group on the bottom chiral carbon.

a. L **b.** D **c.** L

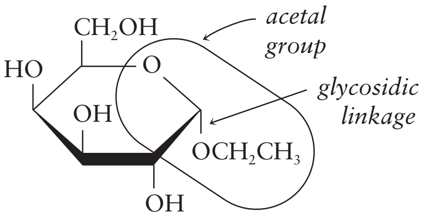
17.6 **a.** aldopentose

b. aldotetrose

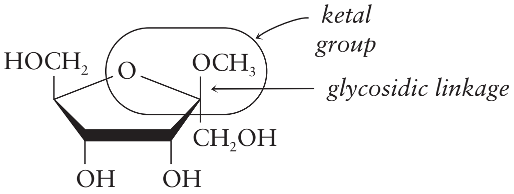
17.7



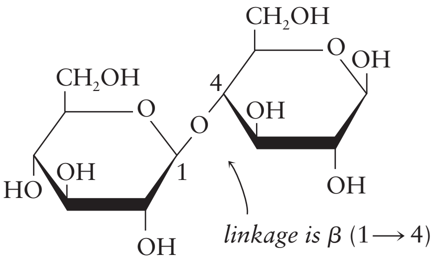
17.8 **a.**



b.



17.9

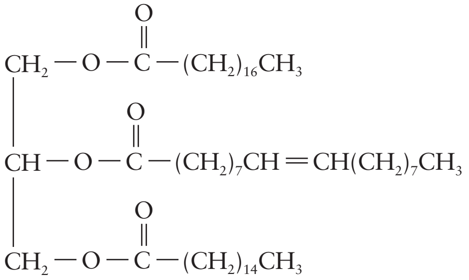


Chapter 18

18.1 With one carbon–carbon double bond, vernolic acid is monounsaturated. Monounsaturated fatty acids, according to Table 18.1, are liquids at room temperature.

18.2 Counting from the left, a carbon part of a double bond is encountered at position 6; this is an omega-6 fatty acid.

18.3 One of several possibilities is the following structure:



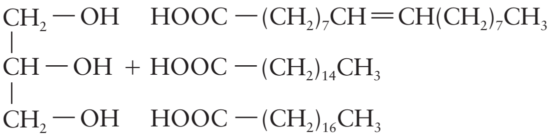
$$\begin{array}{l} \mathrm{CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{16}CH_3} \\ | \\ \mathrm{CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_7CH{=}CH(CH_2)_7CH_3} \\ | \\ \mathrm{CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{14}CH_3} \end{array}$$

(stearic acid component)

(oleic acid component)

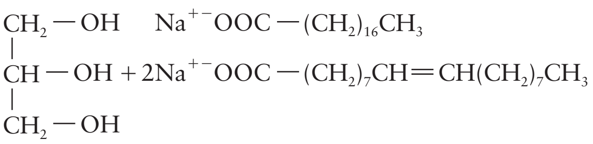
(palmitic acid component)

18.4



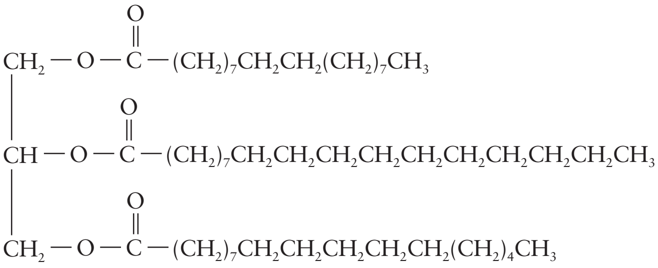
$$\begin{array}{lcl} \mathrm{CH_2-OH} & & \mathrm{HOOC-(CH_2)_7CH{=}CH(CH_2)_7CH_3} \\ | & & \\ \mathrm{CH-OH} & + & \mathrm{HOOC-(CH_2)_{14}CH_3} \\ | & & \\ \mathrm{CH_2-OH} & & \mathrm{HOOC-(CH_2)_{16}CH_3} \end{array}$$

18.5



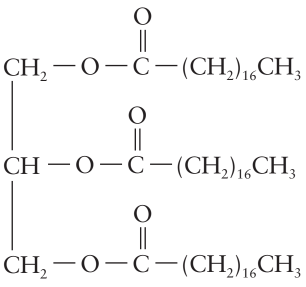
$$\begin{array}{ll} \mathrm{CH_2-OH} & \mathrm{Na^{+}\,{}^{-}OOC-(CH_2)_{16}CH_3} \\ | & \\ \mathrm{CH-OH} & \mathrm{+\,2Na^{+}\,{}^{-}OOC-(CH_2)_7CH{=}CH(CH_2)_7CH_3} \\ | & \\ \mathrm{CH_2-OH} & \end{array}$$

18.6 During complete hydrogenation, all CH═CH groups become $\mathrm{CH_2}$—$\mathrm{CH_2}$ groups:



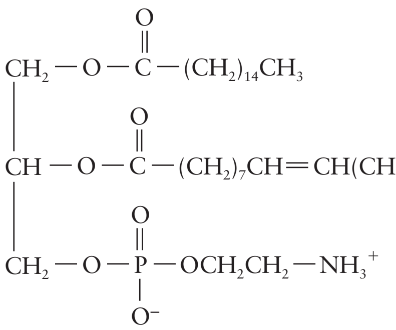
$$\begin{array}{l} \mathrm{CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_7CH_2CH_2(CH_2)_7CH_3} \\ | \\ \mathrm{CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_7CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_2CH_3} \\ | \\ \mathrm{CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_7CH_2CH_2CH_2CH_2CH_2(CH_2)_4CH_3} \end{array}$$

Combining all the $\mathrm{CH_2}$ groups gives:



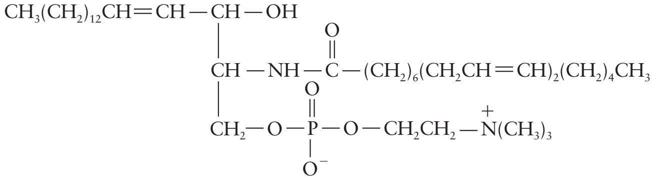
$$\begin{array}{l} \mathrm{CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{16}CH_3} \\ | \\ \mathrm{CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{16}CH_3} \\ | \\ \mathrm{CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{16}CH_3} \end{array}$$

18.7



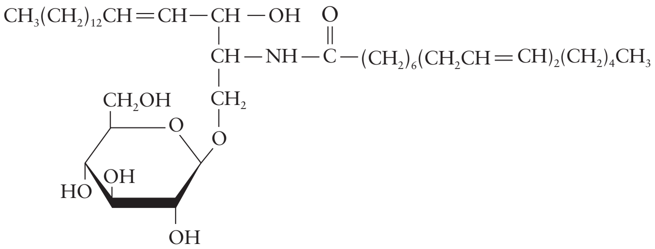
$$\begin{array}{l} \mathrm{CH_2-O-\overset{\overset{O}{\|}}{C}-(CH_2)_{14}CH_3} \\ | \\ \mathrm{CH-O-\overset{\overset{O}{\|}}{C}-(CH_2)_7CH{=}CH(CH_2)_7CH_3} \\ | \\ \mathrm{CH_2-O-\underset{\underset{O^-}{|}}{\overset{\overset{O}{\|}}{P}}-OCH_2CH_2-NH_3^{+}} \end{array}$$

18.8 The structure of a sphingomyelin is constant, except for the fatty acid component.

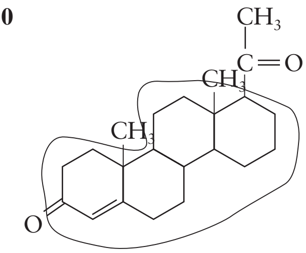


$$\begin{array}{l} \mathrm{CH_3(CH_2)_{12}CH{=}CH-CH-OH} \\ \qquad\qquad\qquad\qquad\quad | \\ \qquad\qquad\qquad\qquad\quad \mathrm{CH-NH-\overset{\overset{O}{\|}}{C}-(CH_2)_6(CH_2CH{=}CH)_2(CH_2)_4CH_3} \\ \qquad\qquad\qquad\qquad\quad | \\ \qquad\qquad\qquad\qquad\quad \mathrm{CH_2-O-\underset{\underset{O^-}{|}}{\overset{\overset{O}{\|}}{P}}-O-CH_2CH_2-\overset{+}{N}(CH_3)_3} \end{array}$$

18.9



18.10



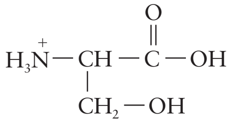
Chapter 19

19.1 a, d

19.2
- **a.** Acidic polar
- **b.** Neutral nonpolar
- **c.** Basic polar
- **d.** Neutral polar

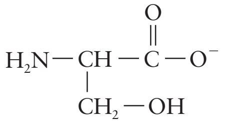
19.3

a.



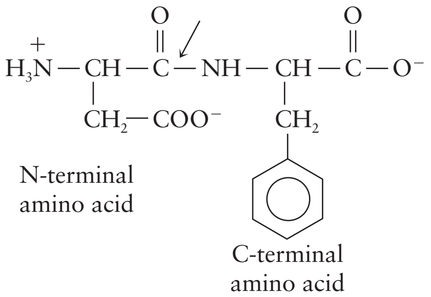
$$\mathrm{H_3\overset{+}{N}-\underset{\underset{CH_2-OH}{|}}{CH}-\overset{\overset{O}{\|}}{C}-OH}$$

b.

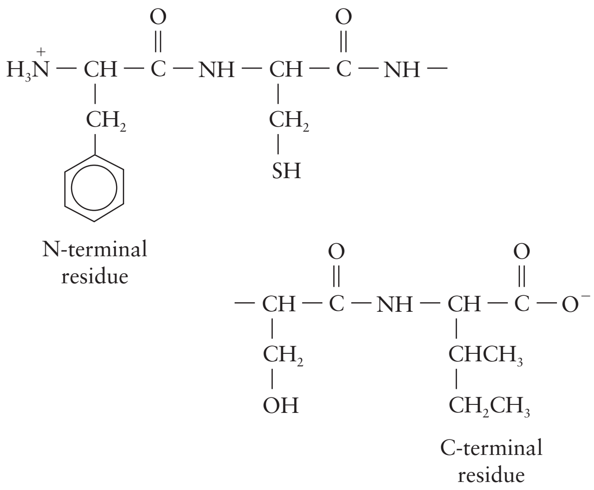


$$\mathrm{H_2N-\underset{\underset{CH_2-OH}{|}}{CH}-\overset{\overset{O}{\|}}{C}-O^-}$$

19.4



19.5



19.6 Gly-Ile-Val-Glu-Glu-Cys-Cys-Thr

19.7 **a.** Hydrophobic attractions between nonpolar groups

b. Hydrogen bonding

c. Salt bridges between the ionic groups

19.8 **a.** Quaternary

b. Secondary

c. Tertiary

Chapter 20

20.1 **a.** maltose

b. peptides

c. glucose-6-phosphate

20.2 Turnover number is the number of substrate molecules acted on per minute by one molecule of enzyme. One enzyme international unit is the amount of enzyme that catalyzes 1 μmol of substrate to react per minute.

20.3 **a.** An increase in enzyme concentration increases the rate of an enzyme-catalyzed reaction.

b. An increase in substrate concentration increases the rate until the enzyme is saturated. Above the saturation point, the rate of reaction is constant.

c. An increase in temperature increases the rate of the enzyme-catalyzed reaction until the optimum temperature is reached. Above the optimum temperature, the rate decreases.

d. An increase in pH increases the reaction rate until the optimum pH is reached. Above the optimum pH, the rate decreases.

20.4 **a.** The structure of a competitive inhibitor resembles that of the substrate. The structure of a noncompetitive inhibitor bears no resemblance to that of the substrate.

b. A competitive inhibitor binds at the active site. A noncompetitive inhibitor binds at some other region of the enzyme.

c. Increasing substrate concentration reverses the effect of a competitive inhibitor, but has no effect on a noncompetitive inhibitor.

20.5 **a.** Several enzymes are synthesized in inactive forms called zymogens. Under the proper reaction conditions, zymogens are activated to carry out their catalytic role.

b. The catalytic ability of allosteric enzymes may be either increased or decreased by the binding of modulators.

c. Certain enzymes are synthesized in greater amounts when needed and in smaller amounts when not needed.

Chapter 21

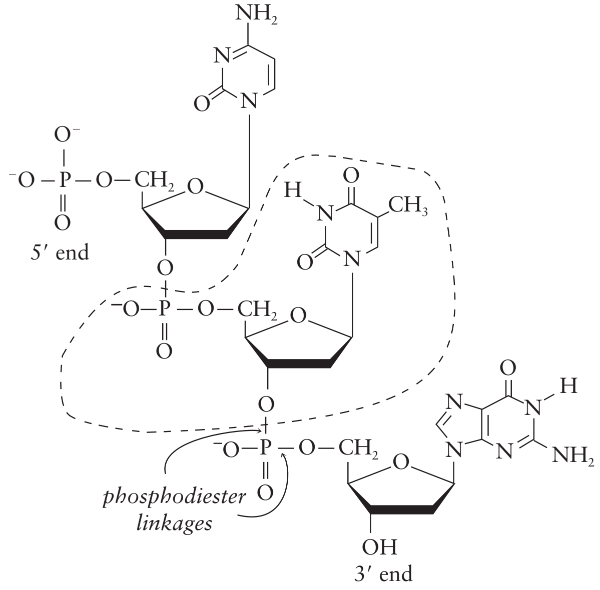
21.1 **a.** Purine, both DNA and RNA

b. Pyrimidine, DNA

21.2 **a.** 1’

b. Phosphate

21.3



21.4 Base pairs A and T are held together by two hydrogen bonds, while G and C share three hydrogen bonds. The total is 13 hydrogen bonds.

21.5 5′ T-T-A-C-G 3′ original strand

3′ A-A-T-G-C 5′ complementary strand

The complementary strand written in the 5′ to 3′ direction is C-G-T-A-A.

21.6 5′ A-T-T-A-G-C-C-G 3′ DNA template

3′ U-A-A-U-C-G-G-C 5′ mRNA

The mRNA written in the 5′ to 3′ direction is C-G-G-C-U-A-A-U.

21.7 f Met-His-His-Val-Leu-Cys

Chapter 22

22.1 **a.** Provide elements for body synthesis.

b. Provide essential fatty acids.

c. Maintenance and repair of cells.

22.2 ADEK

22.3 **a.** Cobalt

b. Flourine

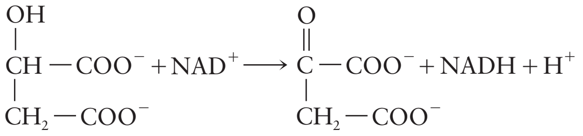
c. Iodine

22.4 **a.** Stage III

b. Stage I

c. Stage II

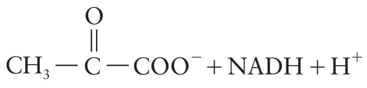
22.5



$$\overset{\displaystyle \mathrm{OH}}{\underset{\displaystyle \mathrm{CH_2-COO^-}}{\mathrm{CH}}}\mathrm{-COO^- + NAD^+ \longrightarrow} \overset{\displaystyle \mathrm{O}}{\underset{\displaystyle \mathrm{CH_2-COO^-}}{\overset{\|}{\mathrm{C}}}}\mathrm{-COO^- + NADH + H^+}$$

22.6 **a.** $^-\mathrm{OOC-CH{=}CH-COO^- + FADH_2}$

b.



$$\mathrm{CH_3-\overset{\displaystyle O}{\overset{\|}{C}}-COO^- + NADH + H^+}$$

Chapter 23

23.1 **a.** Hexokinase regulates the first step of the glycolysis pathway. The enzyme is controlled by concentrations of glucose-6-phosphate through feedback inhibition.

b. Phosphofructokinase is an allosteric enzyme which regulates the production of fructose-1,6-bisphosphate. The enzyme is inhibited by high concentrations of ATP and citrate, and it is activated by high concentrations of ADP and AMP.

c. Pyruvate kinase controls the last step of glycolysis. It is inhibited by higher concentrations of ATP.

23.2 $\mathrm{NAD^+}$ produced from the various fates of pyruvate can be used in the glycolysis pathway, enabling further glycolysis to take place.

23.3 Two enzymes of the citric acid cycle are activated by ADP. When ADP supply is high, the citric acid cycle is stimulated, ultimately resulting in greater production of ATP.

23.4 **a.** Three: Each $\mathrm{FADH_2}$ produces 1.5 molecules of ATP.

b. Five: Each NADH produces 2.5 molecules of ATP.

c. 20: Each acetyl CoA produces 10 molecules of ATP.

23.5 **a.** Two moles ATP

b. Two moles GTP

c. 28 moles ATP

23.6 Glucose-6-phosphatase is present in the liver but not in the muscles.

Chapter 24

24.1 **a.** Each acetyl CoA contains two carbon atoms from capric acid. Thus, five acetyl CoA molecules are formed.

b. Ten carbon atoms require four trips through the fatty acid spiral. Thus, four molecules of $\mathrm{FADH_2}$ are formed.

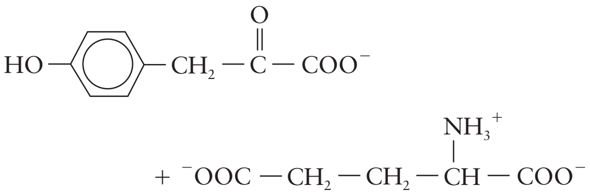
c. Four trips through the spiral also produce four NADH molecules and four $\mathrm{H^+}$ ions.

24.2 A 16-carbon fatty acid would yield eight molecules of acetyl CoA. Seven trips through the spiral are necessary and would produce 7 $\mathrm{FADH_2}$ and 7 NADH +7 $\mathrm{H^+}$.

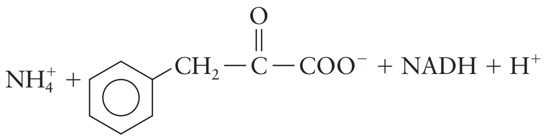
8 acetyl CoA × 10 ATP/acetyl CoA	=	80	ATP
7 $\mathrm{FADH_2}$ × 1.5 ATP/$\mathrm{FADH_2}$	=	10.5	ATP
7 NADH × 2.5 ATP/NADH	=	17.5	ATP
		108	ATP
Two high-energy bonds in ATP are consumed in the activation step.		−2	
		106	ATP

24.3 acetoacetate or β-hydroxybutyrate

24.4



24.5



24.6 **a.** The urea cycle converts toxic ammonia into less toxic urea for excretion from the body.

b. carbamoyl phosphate

24.7 **a.** Pyruvate and intermediates of the citric acid cycle; ultimately glucose.

b. Acetyl CoA and acetoacetyl CoA; ultimately ketone bodies and fatty acids.

24.8 **a.** 9

b. 11

Chapter 25

25.1 **a** $\mathrm{Na^+}$

b. $\mathrm{CI^-}$

c. $\mathrm{HPO_4{}^{2-}}$

25.2 **a.** lungs

b. tissue cells

c. lungs

d. tissue cells

25.3 **a.** creatinine

b. bile pigments

c. glucosuria

25.4 **a.** alkalosis

b. acidosis

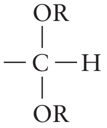
c. alkalosis

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

GLOSSARY

absolute specificity The characteristic of an enzyme that it acts on one and only one substance.

absolute zero The temperature at which all motion stops; a value of 0 on the Kelvin scale.

acetal A compound that contains the  $-\overset{\displaystyle OR}{\underset{\displaystyle OR}{\overset{|}{\underset{|}{C}}}}-H$ arrangement of atoms.

acetone breath A condition in which acetone can be detected in the breath.

acid dissociation constant The equilibrium constant for the dissociation of an acid.

acidic solution A solution in which the concentration of H_3O^+ is greater than the concentration of OH^-. Also, a solution in which pH is less than 7.

acidosis A low blood pH.

activation energy Energy needed to start some spontaneous processes. Once started, the processes continue without further stimulus or energy from an outside source.

activator A substance that binds to an allosteric enzyme and increases its activity.

active site The location on an enzyme where a substrate is bound and catalysis occurs.

activity series A tabular representation of the tendencies of metals to react with H^+.

acute radiation syndrome The condition associated with and following short-term exposure to intense radiation.

addition polymer A polymer formed by the linking together of many alkene molecules through addition reactions.

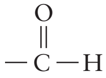
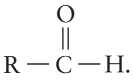
addition reaction A reaction in which a compound adds to a multiple bond.

adipose tissue A kind of connective tissue where triglycerides are stored.

aerobic In the presence of oxygen.

alcohol A compound in which an —OH group is connected to an aliphatic carbon atom.

alcoholic fermentation The conversion of glucose to ethanol.

aldehyde A compound that contains the  $-\overset{\displaystyle O}{\overset{\|}{C}}-H$ group; the general formula is  $R-\overset{\displaystyle O}{\overset{\|}{C}}-H$.

aliphatic compound Any organic compound that is not aromatic.

alkaline solution See **basic solution**.

alkaloids A class of nitrogen-containing organic compounds obtained from plants.

alkalosis An abnormally high blood pH.

alkane A hydrocarbon that contains only single bonds.

alkene A hydrocarbon containing one or more double bonds.

alkoxy group The —O—R functional group.

alkyl group A group differing by one hydrogen from an alkane.

alkyl halide See **haloalkane**.

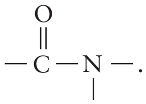
alkyne A hydrocarbon containing one or more triple bonds.

allosteric enzyme An enzyme with a quaternary structure whose activity is changed by the binding of modulators.

alpha-amino acid An organic compound containing both an amino group and a carboxylate group, with the amino group attached to the carbon next to the carboxylate group.

α-helix The helical structure in proteins that is maintained by hydrogen bonds.

alpha particle The particle that makes up alpha rays. It is identical to the helium nucleus and composed of two protons and two neutrons.

amide An organic compound having the functional group  $-\overset{\displaystyle O}{\overset{\|}{C}}-\underset{|}{N}-$.

amide linkage The carbonyl carbon-nitrogen single bond of the amide group.

amine An organic compound derived by replacing one or more of the hydrogen atoms of ammonia with alkyl or aromatic groups, as in RNH_2, R_2NH, and R_3N.

amino acid pool The total supply of amino acids in the body.

amino acid residue An amino acid that is a part of a peptide, polypeptide, or protein chain.

amphetamines A class of drugs structurally similar to epinephrine, used to stimulate the central nervous system.

anabolism All reactions involved in the synthesis of biomolecules.

anaerobic In the absence of oxygen.

anion A negatively charged ion.

anomeric carbon An acetal, ketal, hemiacetal, or hemiketal carbon atom giving rise to two stereoisomers.

anomers Stereoisomers that differ in the three-dimensional arrangement of groups at the carbon of an acetal, ketal, hemiacetal, or hemiketal group.

antibiotic A substance produced by one microorganism that kills or inhibits the growth of other microorganisms.

antibody A substance that helps protect the body from invasion by viruses, bacteria, and other foreign substances.

anticodon A three-base sequence in tRNA that is complementary to one of the codons in mRNA.

antioxidant A substance that prevents another substance from being oxidized.

apoenzyme A catalytically inactive protein formed by removal of the cofactor from an active enzyme.

aromatic hydrocarbon Any organic compound that contains the characteristic benzene ring or similar feature.

Arrhenius acid Any substance that provides H^+ ions when dissolved in water.

Arrhenius base Any substance that provides OH^- ions when dissolved in water.

atom The limit of chemical subdivision for matter.

atomic mass unit (u) A unit used to express the relative masses of atoms. One u is equal to $\frac{1}{12}$ the mass of an atom of carbon-12.

atomic number of an atom A number equal to the number of protons in the nucleus of an atom. Symbolically it is represented by *Z*.

atomic orbital A volume of space around atomic nuclei in which electrons of the same energy move. Groups of orbitals with the same *n* value form subshells.

atomic weight The mass of an average atom of an element expressed in atomic mass units.

Avogadro's law Equal volumes of gases measured at the same temperature and pressure contain equal numbers of molecules.

balanced equation An equation in which the number of atoms of each element in the reactants is the same as the number of atoms of that same element in the products.

basic solution A solution in which the concentration of OH^- is greater than the concentration of H_3O^+. Also, a solution in which pH is greater than 7; also called alkaline solution.

basic unit of measurement A specific unit from which other units for the same quantity are obtained by multiplication or division.

becquerel A physical unit of radiation measurement corresponding to one nuclear disintegration per second.

Benedict's reagent A mild oxidizing solution containing Cu^{2+} ions used to test for the presence of aldehydes.

β-oxidation process A pathway in which fatty acids are broken down into molecules of acetyl CoA.

beta particle The particle that makes up beta rays. It is identical to an electron but is produced in the nucleus when a neutron is changed into a proton and an electron.

β-pleated sheet A secondary protein structure in which protein chains are aligned side by side in a sheetlike array held together by hydrogen bonds.

binary compound A compound made up of two different elements.

biochemistry A study of the compounds and processes associated with living organisms.

biological unit of radiation A radiation measurement unit indicating the damage caused by radiation in living tissue.

biomolecule A general term referring to organic compounds essential to life.

blood sugar level The amount of glucose present in blood, normally expressed as milligrams per 100 mL of blood.

boiling point The temperature at which the vapor pressure of a liquid is equal to the prevailing atmospheric pressure.

bond polarization A result of shared electrons being attracted to the more electronegative atom of a bonded pair of atoms.

Boyle's law A gas law that describes the pressure and volume behavior of a gas sample kept at constant temperature. Mathematically, it is $PV = k$.

branched alkane An alkane in which at least one carbon atom is not part of a continuous chain.

branching chain reaction See **expanding chain reaction**.

breeder reaction A nuclear reaction in which isotopes that will not undergo spontaneous fission are changed into isotopes that will.

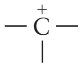
Brønsted acid Any hydrogen-containing substance that is capable of donating a proton (H^+) to another substance.

Brønsted base Any substance that is capable of accepting a proton (H^+) from another substance.

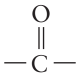
buffer A solution with the ability to resist changing pH when acids (H^+) or bases (OH^-) are added.

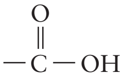
buffer capacity The amount of acid (H^+) or base (OH^-) that can be absorbed by a buffer without causing a significant change in pH.

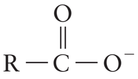
carbaminohemoglobin Hemoglobin combined with carbon dioxide.

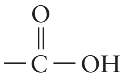
carbocation An ion of the form  $-\overset{+}{\underset{|}{C}}-$.

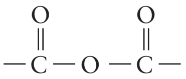
carbohydrate A polyhydroxy aldehyde or ketone, or substance that yields such compounds on hydrolysis.

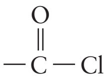
carbonyl group The  $-\overset{\overset{\large O}{\|}}{C}-$ group.

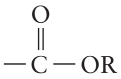
carboxyl group The  $-\overset{\overset{\large O}{\|}}{C}-OH$ group.

carboxylate ion The  $R-\overset{\overset{\large O}{\|}}{C}-O^-$ ion that results from the dissociation of a carboxylic acid.

carboxylic acid An organic compound that contains the  $-\overset{\overset{\large O}{\|}}{C}-OH$ functional group.

carboxylic acid anhydride An organic compound that contains the  $-\overset{\overset{\large O}{\|}}{C}-O-\overset{\overset{\large O}{\|}}{C}-$ functional group.

carboxylic acid chloride An organic compound that contains the  $-\overset{\overset{\large O}{\|}}{C}-Cl$ functional group.

carboxylic ester A compound with the  $-\overset{\overset{\large O}{\|}}{C}-OR$ functional group.

catabolism All reactions involved in the breakdown of biomolecules.

catalyst A substance that changes (usually increases) reaction rates without being used up in the reaction.

cation A positively charged ion.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

cellular respiration The entire process involved in the use of oxygen by cells.

central dogma of molecular biology The well-established process by which genetic information stored in DNA molecules is expressed in the structure of synthesized proteins.

cephalin A phosphoglyceride containing ethanolamine or serine.

chain reaction A nuclear reaction in which the products of one reaction cause a repeat of the reaction to take place. In the case of uranium fission, neutrons from fission reactions cause other fission reactions to occur.

Charles's law A gas law that describes the temperature and volume behavior of a gas sample kept at constant pressure. Mathematically, it is $V/T = k'$.

chemical changes Changes matter undergoes that involve changes in composition.

chemical properties Properties that matter demonstrates when attempts are made to change it into new substances.

chemiosmotic hypothesis The postulate that a proton flow across the inner mitochondrial membrane during operation of the electron transport chain provides energy for ATP synthesis.

chiral A descriptive term for compounds or objects that cannot be superimposed on their mirror image.

chiral carbon A carbon atom with four different groups attached.

chloride shift The movement of chloride ions from one fluid to another to maintain charge neutrality.

chromosome A tightly packed bundle of DNA and protein that is involved in cell division.

chylomicron A lipoprotein aggregate found in the lymph and the bloodstream.

cis- On the same side (as applied to *cis-trans* isomers).

***cis-trans* isomers** Molecules with restricted rotation around C—C bonds that differ in the three-dimensional arrangements of their atoms in space and not in the order of linkage of atoms.

citric acid cycle A series of reactions in which acetyl CoA is oxidized to carbon dioxide and reduced forms of coenzymes FAD and NAD^+ are produced.

codon A sequence of three nucleotide bases that represents a code word on mRNA molecules.

coenzyme An organic molecule required by an enzyme for catalytic activity.

cofactor A nonprotein molecule or ion required by an enzyme for catalytic activity.

cohesive forces The attractive force between particles; they are associated with potential energy.

cold spot Tissue from which a radioactive tracer is excluded or rejected.

colligative property A solution property that depends only on the concentration of solute particles in solution.

colloid A homogeneous mixture of two or more substances in which the dispersed substances are present as larger particles than are found in solutions.

combination reaction A chemical reaction in which two or more substances react to form a single substance.

combined gas law A gas law that describes the pressure, volume, and temperature behavior of a gas sample. Mathematically, it is $PV/T = k''$.

common catabolic pathway The reactions of the citric acid cycle plus those of the electron transport chain and oxidative phosphorylation.

competitive inhibitor An inhibitor that competes with substrate for binding at the active site of an enzyme.

complementary DNA strands Two strands of DNA in a double-helical form such that adenine and guanine of one strand are matched and hydrogen bonded to thymine and cytosine, respectively, of the second strand.

complete protein Protein in food that contains all essential amino acids in the proportions needed by the body.

complex carbohydrates The polysaccharides amylose and amylopectin, collectively called starch.

complex lipid An ester-containing lipid with more than two types of components: an alcohol, fatty acids—plus others.

compound A pure substance consisting of two or more kinds of atoms in the form of heteroatomic molecules or individual atoms.

compound formula A representation of the molecule of a compound, consisting of the symbols of the atoms found in the molecule. Atoms present in numbers greater than one have the number indicated by a subscript.

compressibility The change in volume of a sample resulting from a pressure change acting on the sample.

concentration The relationship between the amount of solute and the specific amount of solution in which it is contained.

condensation An exothermic process in which a gas or vapor is changed to a liquid or solid.

condensation polymerization The process by which monomers combine with the simultaneous elimination of a small molecule.

condensed structural formula A structural molecular formula showing the general arrangement of atoms but without showing all the covalent bonds.

conformations The different arrangements of atoms in space achieved by rotation about single bonds.

conjugate acid–base pair A Brønsted acid and its conjugate base.

conjugate base The species remaining when a Brønsted acid donates a proton.

conjugated protein A protein made up of amino acid residues and other organic or inorganic components.

copolymer An addition polymer formed by the reaction of two different monomers.

Cori cycle The process in which glucose is converted to lactate in muscle tissue, lactate is reconverted to glucose in the liver, and glucose is returned to the muscle.

covalent bond The attractive force that results between two atoms that are both attracted to a shared pair of electrons.

critical mass The minimum amount of fissionable material needed to sustain a critical chain reaction at a constant rate.

critical reaction A constant-rate chain reaction.

crystal lattice A rigid three-dimensional arrangement of particles.

C-terminal residue An amino acid on the end of a chain that has an unreacted or free carboxylate group.

curie A physical unit of radiation measurement corresponding to 3.7×10^{10} nuclear disintegrations per second.

cycloalkane An alkane in which carbon atoms form a ring.

cyclotron A cyclic particle accelerator that works by changing electrical polarities as charged particles cross a gap. The particles are kept in a spiral path by a strong magnetic field.

cytochrome An iron-containing enzyme located in the electron transport chain.

Daily Reference Values (DRVs) A set of standards for nutrients and food components (such as fat and fiber) that have important relationships with health; used on food labels as part of the Daily Values.

Daily Values (DVs) Reference values developed by the FDA specifically for use on food labels. The Daily Values represent two sets of standards: Reference Daily Intakes (RDIs) and Daily Reference Values (DRVs).

Dalton's law of partial pressures The total pressure exerted by a mixture of gases is equal to the sum of the partial pressures of the gases in the mixture.

daughter nuclei The new nuclei produced when unstable nuclei undergo radioactive decay.

decomposition A change in chemical composition that can result from heating.

decomposition reaction A chemical reaction in which a single substance reacts to form two or more simpler substances.

dehydration reaction A reaction in which water is chemically removed from a compound.

denaturation The process by which a protein loses its characteristic native structure and function.

density The number given when the mass of a sample of a substance is divided by the volume of the same sample.

deoxyhemoglobin (hemoglobin) Nonoxygenated hemoglobin.

deoxyribonucleic acid (DNA) A nucleic acid found primarily in the nuclei of cells.

derived unit of measurement A unit obtained by multiplication or division of one or more basic units.

dextrorotatory Rotates plane-polarized light to the right.

dialysis A process in which solvent molecules, other small molecules, and hydrated ions pass from a solution through a membrane.

dialyzing membrane A semipermeable membrane with pores large enough to allow solvent molecules, other small molecules, and hydrated ions to pass through.

diatomic molecules Molecules that contain two atoms.

diffusion A process that causes substances to spontaneously intermingle when they are brought together.

dimer Two identical molecules bonded together.

dipeptide A compound formed when two amino acids are bonded by an amide linkage.

dipolar force The attractive force that exists between the positive end of one polar molecule and the negative end of another.

diprotic acid An acid that gives up two protons (H^+) per molecule when dissolved.

disaccharide A carbohydrate formed by the combination of two monosaccharide units.

dispersed phase The substance present in a colloidal dispersion in amounts less than the amount of the dispersing medium.

dispersing medium The substance present in a colloidal dispersion in the largest amount.

dispersion forces Very weak attractive forces acting between the particles of all matter. They result from momentary nonsymmetric electron distributions in molecules or atoms.

disruptive forces The force resulting from particle motion; they are associated with kinetic energy.

dissolving A term used to describe the process of solution formation when one or more solutes are dispersed in a solvent to form a homogeneous mixture.

distinguishing electron The last and highest-energy electron found in an element.

disulfide A compound containing an $-S-S-$ group.

disulfide bridge A bond produced by the oxidation of $-SH$ groups on two cysteine residues. The bond loops or holds two peptide chains together.

double bond The bond resulting from the sharing of two pairs of electrons.

double-replacement reaction A chemical reaction in which two compounds react and exchange partners to form two new compounds.

effective collision A collision that causes a reaction to occur between colliding molecules.

effusion A process in which a gas escapes from a container through a small hole.

electrolyte A solute that when dissolved in water forms a solution that conducts electricity.

electron capture A mode of decay for some unstable nuclei in which an electron from outside the nucleus is drawn into the nucleus, where it combines with a proton to form a neutron.

electronic configurations The detailed arrangement of electrons indicated by a specific notation, $1s^2 2s^2 2p^4$, etc.

electron transport chain A series of reactions in which protons and electrons from the oxidation of foods are used to reduce molecular oxygen to water.

electronegativity The tendency of an atom to attract shared electrons of a covalent bond.

element A pure substance consisting of only one kind of atom in the form of homoatomic molecules or individual atoms.

elemental symbol A symbol assigned to an element based on the name of the element, consisting of one capital letter or a capital letter followed by a lowercase letter.

elimination reaction A reaction in which two or more covalent bonds are broken and a new multiple bond is formed.

emulsifying agent (stabilizing agent) A substance that when added to colloids prevents them from coalescing and settling.

enantiomers Stereoisomers that are mirror images.

endergonic process A process that gains or accepts energy as it takes place.

endothermic reaction A reaction that absorbs heat.

endpoint of a titration The point at which the titration is stopped on the basis of an indicator color change or pH meter reading.

entropy A measurement or indication of the disorder or randomness of a system. The more disorderly a system is, the higher its entropy.

enzyme A biomolecule that catalyzes chemical reactions.

enzyme activity The rate at which an enzyme catalyzes a reaction.

enzyme induction The synthesis of an enzyme in response to a cellular need.

enzyme inhibitor A substance that decreases the activity of an enzyme.

enzyme international unit (IU) A quantity of enzyme that catalyzes the conversion of 1 μmol of substrate per minute under specified conditions.

equilibrium concentrations The unchanging concentrations of reactants and products in a reaction system that is in a state of equilibrium.

equilibrium constant A numerical relationship between reactant and product concentrations in a reaction at equilibrium.

equilibrium expression An equation relating the equilibrium constant and reactant and product equilibrium concentrations.

equivalence point of a titration The point at which the unknown solution has exactly reacted with the known solution. Neither is in excess.

equivalent of salt The amount that will produce 1 mol of positive (or negative) electrical charges when dissolved and dissociated.

essential amino acid An amino acid that cannot be synthesized within the body at a rate adequate to meet metabolic needs.

essential fatty acid A fatty acid needed by the body but not synthesized within the body.

ester A compound in which the —OH of an acid is replaced by an —OR.

ester linkage The carbonyl carbon–oxygen single bond of the ester group.

esterification The process of forming an ester.

ether A compound that contains a $-\underset{|}{\overset{|}{\mathrm{C}}}-\mathrm{O}-\underset{|}{\overset{|}{\mathrm{C}}}-$ functional group.

eukaryotic cell A cell containing membrane-enclosed organelles, particularly a nucleus.

evaporation An endothermic process in which a liquid is changed to a gas; also called vaporization.

exact numbers Numbers that have no uncertainty; numbers from defined relationships, counting numbers, and numbers that are part of simple fractions.

exergonic process A process that gives up energy as it takes place.

exon A segment of a eukaryotic DNA molecule that is coded for amino acids.

exothermic reaction A reaction that liberates heat.

expanded structural formula A structural molecular formula showing all the covalent bonds.

expanding chain reaction A reaction in which the products of one reaction cause more than one more reaction to occur; also called branching chain reaction.

extracellular fluid Body fluid located outside cells.

factors used in the factor-unit method Fractions obtained from numerical relationships between quantities.

family of the periodic table See **group of the periodic table.**

fat A triglyceride that is a solid at room temperature.

fat mobilization The hydrolysis of stored triglycerides, followed by the entry of fatty acids and glycerol into the bloodstream.

fatty acid A long-chain carboxylic acid found in fats.

feedback inhibition A process in which the end product of a sequence of enzyme-catalyzed reactions inhibits an earlier step in the process.

fermentation A reaction of sugars, starch, or cellulose to produce ethanol and carbon dioxide.

fibrous protein A protein made up of long rod-shaped or stringlike molecules that intertwine to form fibers.

first ionization energy The energy required to remove the first electron from a neutral atom.

Fischer projection A method of depicting three-dimensional shapes for chiral molecules.

fluid-mosaic model A model of membrane structure in which proteins are embedded in a flexible lipid bilayer.

formula weight The sum of the atomic weights of the atoms shown in the formula of an ionic compound.

functional group A unique reactive combination of atoms that differentiates molecules of organic compounds of one class from those of another.

furanose ring A five-membered sugar ring system containing an oxygen atom.

gamma ray A high-energy ray that is like an X-ray, but with a higher energy.

gas laws Mathematical relationships that describe the behavior of gases as they are mixed, subjected to pressure or temperature changes, or allowed to diffuse.

Geiger–Müller tube A radiation-detection device operating on the principle that ions form when radiation passes through a tube filled with low-pressure gas.

gene An individual section of a chromosomal DNA molecule that is the fundamental unit of heredity.

genome A summation of all the genetic material (chromosomes) of a cell; a person's genetic blueprint.

globular protein A spherical protein that usually forms stable suspensions in water or dissolves in water.

glucogenic amino acid An amino acid whose carbon skeleton can be converted metabolically to an intermediate used in the synthesis of glucose.

gluconeogenesis The synthesis of glucose from noncarbohydrate molecules.

glucosuria A condition in which elevated blood sugar levels result in the excretion of glucose in the urine.

glycogenesis The synthesis of glycogen from glucose.

glycogenolysis The breakdown of glycogen to glucose.

glycolipid A complex lipid containing a sphingosine, a fatty acid, and a carbohydrate.

glycolysis A series of reactions by which glucose is oxidized to pyruvate.

glycoside Another name for a carbohydrate containing an acetal or ketal group.

glycosidic linkage The carbon–oxygen–carbon linkage that joins the components of a glycoside to the ring.

Graham's law A mathematical expression that relates rates of effusion or diffusion of two gases to the masses of the molecules of the two gases.

gray A biological unit of radiation measurement corresponding to the transfer of 1 J of energy to 1 kg of tissue.

group of the periodic table A vertical column of elements that have similar chemical properties; also called family of the periodic table.

half-life The time required for one-half the unstable nuclei in a sample to undergo radioactive decay.

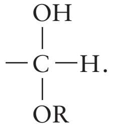
haloalkane A derivative of an alkane in which one or more hydrogens are replaced by halogens; also called alkyl halide.

Haworth structure A method of depicting three-dimensional carbohydrate structures.

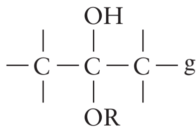
heat of fusion The amount of heat energy required to melt exactly 1 g of a solid substance at constant temperature.

heat of vaporization The amount of heat energy required to vaporize exactly 1 g of a liquid substance at constant temperature.

hemiacetal A compound that contains the functional group



$$-\overset{\text{OH}}{\underset{\text{OR}}{\text{C}}}-\text{H}.$$

hemiketal A compound that contains the  $-\text{C}-\overset{\text{OH}}{\underset{\text{OR}}{\text{C}}}-\text{C}-$ group.

Henderson–Hasselbalch equation A relationship between the pH of a buffer, pK_a, and the concentrations of acid and salt in the buffer.

heteroatomic molecules Molecules that contain two or more kinds of atoms.

heterocyclic ring A ring containing at least one atom of an element other than carbon.

heterogeneous catalyst A catalytic substance normally used in the form of a solid with a large surface area on which reactions take place; also called surface catalyst.

heterogeneous matter Matter with properties that are not the same throughout the sample.

heterogeneous nuclear RNA (hnRNA) RNA produced when both introns and exons of eukaryotic cellular DNA are transcribed.

high-energy compound A substance that on hydrolysis liberates a great amount of free energy.

homeostasis A condition of chemical balance in the body.

homoatomic molecules Molecules that contain only one kind of atom.

homogeneous catalyst A catalytic substance that is distributed uniformly throughout the reaction mixture.

homogeneous matter Matter that has the same properties throughout the sample.

homologous series Compounds of the same functional class that differ by a $-CH_2-$ group.

hormone A chemical messenger secreted by specific glands and carried by the blood to a target tissue, where it triggers a particular response.

hot spot Tissue in which a radioactive tracer concentrates.

Hund's rule A statement of the behavior of electrons when they occupy orbitals: Electrons will not join other electrons in an orbital if an empty orbital of the same energy is available for occupancy.

hybrid orbital An orbital produced from the combination of two or more nonequivalent orbitals of an atom.

hydrate A salt that contains specific numbers of water molecules as part of the solid crystalline structure.

hydrated ions Ions in solution that are surrounded by water molecules.

hydration The addition of water to a multiple bond.

hydrocarbon An organic compound that contains only carbon and hydrogen.

hydrogenation A reaction in which the addition of hydrogen takes place.

hydrogen bonding The result of attractive dipolar forces between molecules in which hydrogen atoms are covalently bonded to very electronegative elements (O, N, or F).

hydrolysis Bond breakage by reaction with water.

hydrolysis reaction Any reaction with water. For salts it is a reaction of the acidic cation and/or basic anion of the salt with water.

hydrophobic Molecules or parts of molecules that repel (are insoluble in) water.

hydroxy group The $-OH$ functional group.

hyperglycemia A higher-than-normal blood sugar level.

hyperventilation Rapid, deep breathing.

hypoglycemia A lower-than-normal blood sugar level.

hypoventilation Slow, shallow breathing.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

ideal gas law A gas law that relates the pressure, volume, temperature, and number of moles in a gas sample. Mathematically, it is $PV = nRT$.

immiscible A term used to describe liquids that are insoluble in each other.

induced-fit theory A theory of enzyme action proposing that the conformation of an enzyme changes to accommodate an incoming substrate.

inhibitor A substance that decreases reaction rates.

inner-transition element An element in which the distinguishing electron is found in an *f* subshell.

inorganic chemistry The study of the elements and all noncarbon compounds.

insoluble substance A substance that does not dissolve to a significant extent in a solvent.

internal energy The energy associated with vibrations within molecules.

International Unit (IU) A measure of vitamin activity, determined by biological methods.

interstitial fluid The fluid surrounding individual tissue cells.

intracellular fluid Body fluid located inside cells.

intron A segment of a eukaryotic DNA molecule that carries no codes for amino acids.

inverse square law of radiation A mathematical way of saying that the intensity of radiation is inversely proportional to the square of the distance from the source of the radiation.

invert sugar A mixture of equal amounts of glucose and fructose.

ionic bond The attractive force that holds together ions of opposite charge.

ion product of water The equilibrium constant for the dissociation of pure water into H_3O^+ and OH^-.

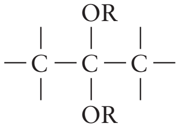
isoelectric point The characteristic solution pH at which an amino acid has a net charge of zero.

isoelectronic A term that literally means "same electronic," used to describe atoms or ions that have identical electronic configurations.

isoenzyme A slightly different form of the same enzyme produced by different tissues.

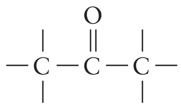
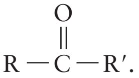
isomerism A property in which two or more compounds have the same molecular formula but different arrangements of atoms.

isotopes Atoms that have the same atomic number but different mass numbers. That is, they are atoms of the same element that contain different numbers of neutrons in their nuclei.

ketal A compound that contains the  $-\overset{|}{\underset{|}{\mathrm{C}}}-\overset{\mathrm{OR}}{\underset{\mathrm{OR}}{\mathrm{C}}}-\overset{|}{\underset{|}{\mathrm{C}}}-$ group.

ketoacidosis A low blood pH due to elevated levels of ketone bodies.

ketogenic amino acid An amino acid whose carbon skeleton can be converted metabolically to acetyl CoA or acetoacetyl CoA.

ketone A compound that contains the  $-\overset{|}{\underset{|}{\mathrm{C}}}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\overset{|}{\underset{|}{\mathrm{C}}}-$ group; the general formula is  $\mathrm{R}-\overset{\mathrm{O}}{\overset{\|}{\mathrm{C}}}-\mathrm{R'}$.

ketone bodies Three compounds—acetoacetate, β-hydroxybutyrate, and acetone—formed from acetyl CoA.

ketonemia An elevated level of ketone bodies in the blood.

ketonuria The presence of ketone bodies in the urine.

ketosis A condition in which ketonemia, ketonuria, and acetone breath exist together.

kinetic energy The energy a particle has as a result of its motion. Mathematically, it is $\mathrm{KE} = \frac{1}{2}mv^2$.

lactate fermentation The production of lactate from glucose.

lattice site The individual location occupied by a particle in a crystal lattice.

law of conservation of matter Atoms are neither created nor destroyed in chemical reactions.

Le Châtelier's principle The position of an equilibrium shifts in response to changes made in factors of the equilibrium.

lecithin A phosphoglyceride containing choline.

levorotatory Rotates plane-polarized light to the left.

Lewis structure A representation of an atom or ion in which the elemental symbol represents the atomic nucleus and all but the valence-shell electrons. The valence-shell electrons are represented by dots arranged around the elemental symbol.

limiting reactant The reactant that is completely used up first in a reaction, based on the amount of each reactant initially present and the combining ratio. It is the reactant that determines the amount of product formed.

limiting-reactant principle The amount of product possible is determined by the amount of each reactant present and the combining ratio.

linear accelerator A particle accelerator that works by changing electrical polarities as charged particles cross gaps between segments of a long tube.

lipid A biological compound that is soluble only in nonpolar solvents.

lipid bilayer A structure found in membranes, consisting of two sheets of lipid molecules arranged so that the hydrophobic portions are facing each other.

lock-and-key theory A theory of enzyme specificity proposing that a substrate has a shape fitting that of the enzyme's active site, as a key fits a lock.

macronutrient A substance needed by the body in relatively large amounts.

major mineral A mineral found in the body in quantities greater than 5 g.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Markovnikov's rule In the addition of H—X to an alkene, the hydrogen becomes attached to the carbon atom that is already bonded to more hydrogens.

mass A measurement of the amount of matter in an object.

mass number of an atom A number equal to the sum of the number of protons and neutrons in the nucleus of an atom. Symbolically it is represented by *A*.

matter Anything that has mass and occupies space.

melting point The temperature at which a solid changes to a liquid; the solid and liquid have the same vapor pressure.

messenger RNA (mRNA) RNA that carries genetic information from the DNA in the cell nucleus to the site of protein synthesis in the cytoplasm.

metabolic acidosis A condition of acidosis resulting from causes other than hypoventilation.

metabolic alkalosis A condition of alkalosis resulting from causes other than hyperventilation.

metabolic pathway A sequence of reactions used to produce one product or accomplish one process.

metabolism The sum of all reactions occurring in an organism.

metallic bond An attractive force responsible for holding solid metals together. It originates from the attraction between positively charged atomic kernels that occupy the lattice sites and mobile electrons that move freely through the lattice.

metalloids Elements that form a narrow diagonal band in the periodic table between metals and nonmetals. They have properties somewhat between those of metals and nonmetals.

metals Elements found in the left two-thirds of the periodic table. Most have the following properties: high thermal and electrical conductivities, high malleability and ductility, and a metallic luster.

micelle A spherical cluster of molecules in which the polar portions of the molecules are on the surface and the nonpolar portions are located in the interior.

micronutrient A substance needed by the body only in small amounts.

mineral A metal or nonmetal used in the body in the form of ions or compounds.

mitochondrion A cellular organelle where reactions of the common catabolic pathway occur.

mixture A physical blend of matter that can theoretically be physically separated into two or more components.

moderators Materials capable of slowing down neutrons that pass through them.

modulator A substance that binds to an enzyme at a location other than the active site and alters the catalytic activity.

molarity (M) A solution concentration expressed in terms of the number of moles of solute contained in a liter of solution.

mole The number of particles (atoms or molecules) contained in a sample of an element or compound with a mass in grams equal to the atomic or molecular weight, respectively. Numerically, 1 mol is equal to 6.022×10^{23} particles.

molecular equation An equation written with each compound represented by its formula.

molecular weight The relative mass of a molecule expressed in atomic mass units and calculated by adding together the atomic weights of the atoms in the molecule.

molecule The smallest particle of a pure substance that has the properties of that substance and is capable of a stable independent existence. Alternatively, a molecule is the limit of physical subdivision for a pure substance.

monomer The starting material that becomes the repeating units of polymers.

monoprotic acid An acid that gives up only one proton (H^+) per molecule when dissolved.

monosaccharide A simple carbohydrate most commonly consisting of three to six carbon atoms.

mutagen A chemical that induces mutations by reacting with DNA.

mutation Any change resulting in an incorrect base sequence on DNA.

native state The natural three-dimensional conformation of a functional protein.

net ionic equation An equation that contains only un-ionized or insoluble materials and ions that undergo changes as the reaction proceeds. All spectator ions are eliminated.

network solids Solids in which the lattice sites are occupied by atoms that are covalently bonded to each other.

neurotransmitter A substance that acts as a chemical bridge in nerve impulse transmission between nerve cells.

neutral A term used to describe any water solution in which the concentrations of H_3O^+ and OH^- are equal. Also, a water solution with $pH = 7$.

neutralization reaction A reaction in which an acid and base react completely, leaving a solution that contains only a salt and water.

noble gas configuration An electronic configuration in which the last eight electrons occupy and fill the *s* and *p* subshells of the highest-occupied shell.

noncompetitive inhibitor An inhibitor that binds to the enzyme at a location other than the active site.

nonelectrolyte A solute that when dissolved in water forms a solution that does not conduct electricity.

nonessential amino acid An amino acid that can be synthesized within the body in adequate amounts.

nonmetals Elements found in the right one-third of the periodic table. They often occur as brittle, powdery solids or gases and have properties generally opposite those of metals.

nonpolar covalent bond A covalent bond in which the bonding pair of electrons is shared equally by the bonded atoms.

nonpolar molecule A molecule that contains no polarized bonds, or a molecule containing polarized bonds in which the resulting charges are distributed symmetrically throughout the molecule.

normal alkane Any alkane in which all the carbon atoms are aligned in a continuous chain.

normal boiling point The temperature at which the vapor pressure of a liquid is equal to 1 standard atmosphere (760 torr); also called standard boiling point.

N-terminal residue An amino acid on the end of a chain that has an unreacted or free amino group.

nuclear fission A process in which large nuclei split into smaller, approximately equal-sized nuclei when bombarded by neutrons.

nuclear fusion A process in which small nuclei combine or fuse to form larger nuclei.

nucleic acid A biomolecule involved in the transfer of genetic information from existing cells to new cells.

nucleic acid backbone The sugar–phosphate chain that is common to all nucleic acids.

nucleotide The repeating structural unit or monomer of polymeric nucleic acids.

nucleus The central core of atoms that contains protons, neutrons, and most of the mass of atoms.

nutrition An applied science that studies food, water, and other nutrients and the ways living organisms use them.

octet rule A rule for predicting electron behavior in reacting atoms. It says that atoms will gain or lose sufficient electrons to achieve an outer electron arrangement identical to that of a noble gas. This arrangement usually consists of eight electrons in the valence shell.

oil A triglyceride that is a liquid at room temperature.

Okazaki fragment A DNA fragment produced during replication as a result of strand growth in a direction away from the replication fork.

optically active molecule A molecule that rotates the plane of polarized light.

optimum pH The pH at which enzyme activity is highest.

optimum temperature The temperature at which enzyme activity is highest.

organelle A specialized structure within a cell that performs a specific function.

organic chemistry The study of carbon-containing compounds.

organic compound A compound that contains the element carbon.

osmolarity The product of n and M in the equation $\pi = nMRT$.

osmosis The process in which solvent flows through a semipermeable membrane into a solution.

osmotic pressure The hydrostatic pressure required to prevent the net flow of solvent through a semipermeable membrane into a solution.

oxidation Originally, a process involving a reaction with oxygen. Today it means a number of things, including a process in which electrons are given up, hydrogen is lost, or an oxidation number increases.

oxidation numbers Positive or negative numbers assigned to the elements in chemical formulas according to a specific set of rules; also called oxidation states.

oxidation states See **oxidation numbers**.

oxidative deamination An oxidation process resulting in the removal of an amino group.

oxidative phosphorylation A process coupled with the electron transport chain whereby ADP is converted to ATP.

oxidizing agent The substance that contains an element that is reduced during a chemical reaction.

oxyhemoglobin Hemoglobin combined with oxygen.

partial pressure The pressure an individual gas of a mixture would exert if it were in the container alone at the same temperature as the mixture.

Pauli exclusion principle A statement of the behavior of electrons when they occupy orbitals: Only electrons spinning in opposite directions can simultaneously occupy the same orbital.

peptide An amino acid polymer of short chain length.

peptide linkage (peptide bond) The amide linkage between amino acids that results when the amino group of one acid reacts with the carboxylate group of another.

percent A solution concentration that expresses the amount of solute in 100 parts of solution.

percentage yield The percentage of the theoretical amount of a product actually produced by a reaction.

period of the periodic table A horizontal row of elements.

periodic law A statement about the behavior of the elements when they are arranged in a specific order. In its present form, it is stated as follows: Elements with similar chemical properties occur at regular (periodic) intervals when the elements are arranged in order of increasing atomic numbers.

pH The negative logarithm of the molar concentration of H^+ (H_3O^+) in a solution.

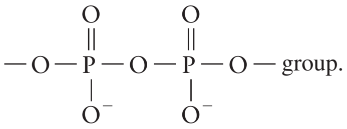
phenol A compound in which an —OH group is connected to a benzene ring. The parent compound is also called phenol.

phenyl group A benzene ring with one hydrogen absent, C_6H_5—.

phosphoglyceride A complex lipid containing glycerol, fatty acids, phosphoric acid, and an alcohol component.

phospholipid A phosphorus-containing lipid.

phosphoric anhydride A compound that contains the



$$-\mathrm{O}-\underset{\mathrm{O}^-}{\underset{|}{\overset{\mathrm{O}}{\overset{\|}{\mathrm{P}}}}}-\mathrm{O}-\underset{\mathrm{O}^-}{\underset{|}{\overset{\mathrm{O}}{\overset{\|}{\mathrm{P}}}}}-\mathrm{O}-\ \text{group.}$$

physical changes Changes matter undergoes without changing composition.

physical properties Properties of matter that can be observed or measured without trying to change the composition of the matter being studied.

physical unit of radiation A radiation measurement unit indicating the activity of the source of the radiation; for example, the number of nuclear decays per minute.

pK_a The negative logarithm of K_a.

plasma The liquid portion of whole blood.

plasmid Circular, double-stranded DNA found in the cytoplasm of bacterial cells.

polar covalent bond A covalent bond that shows bond polarization; that is, the bonding electrons are shared unequally.

polar molecule A molecule that contains polarized bonds and in which the resulting charges are distributed nonsymmetrically throughout the molecule.

polyatomic ions Covalently bonded groups of atoms that carry a net electrical charge.

polyatomic molecules Molecules that contain three or more atoms.

polycyclic aromatic compound A derivative of benzene in which carbon atoms are shared between two or more benzene rings.

polyfunctional compound A compound with two or more functional groups.

polymer A very large molecule made up of repeating units.

polymerization A reaction that produces a polymer.

polypeptide An amino acid polymer of intermediate chain length containing up to 50 amino acid residues.

polyribosome A complex of mRNA and several ribosomes; also called polysome.

polysaccharide A carbohydrate formed by the combination of many monosaccharide units.

polysome See **polyribosome**.

polyunsaturated A term usually applied to molecules with several double bonds.

position of equilibrium An indication of the relative amounts of reactants and products present at equilibrium.

positron A positively charged electron.

potential energy The energy a particle has as a result of attractive or repulsive forces acting on it.

pressure A force per unit area of surface on which the force acts. In measurements and calculations involving gases, it is often expressed in units related to measurements of atmospheric pressure.

primary alcohol An alcohol in which the OH group is attached to CH_3 or to a carbon attached to one other carbon atom.

primary amine An amine having one alkyl or aromatic group bonded to nitrogen, as in $R{-}NH_2$.

primary protein structure The linear sequence of amino acid residues in a protein chain.

products of a reaction The substances produced as a result of the reaction taking place. They are written on the right side of the equation representing the reaction.

prokaryotic cell A simple unicellular organism that contains no nucleus and no membrane-enclosed organelles.

prostaglandin A substance derived from unsaturated fatty acids, with hormonelike effects on a number of body tissues.

prosthetic group The non-amino acid parts of conjugated proteins.

protein An amino acid polymer made up of more than 50 amino acids.

protein turnover The continuing process in which body proteins are hydrolyzed and resynthesized.

pure substance Matter that has a constant composition and fixed properties.

pyranose ring A six-membered sugar ring system containing an oxygen atom.

quaternary ammonium salt An ionic compound containing a positively charged ion in which four alkyl or aromatic groups are bonded to nitrogen, as in R_4N^+.

quaternary protein structure The arrangement of subunits that form a larger protein.

rad A biological unit of radiation measurement corresponding to the transfer of 1×10^{-2} J or 2.4×10^{-3} cal of energy to 1 kg of tissue.

radical An electron-deficient particle that is very reactive; also called free radical.

radioactive dating A process for determining the age of artifacts and rocks, based on the amount and half-life of radioisotopes contained in the object.

radioactive decay A process in which an unstable nucleus changes energy states and in the process emits radiation.

radioactive nuclei Nuclei that undergo spontaneous changes and emit energy in the form of radiation.

radioisotope An isotope of an element that emits nuclear radiation.

reactants of a reaction The substances that undergo chemical change during the reaction. They are written on the left side of the equation representing the reaction.

reaction mechanism A detailed explanation of how a reaction actually takes place.

reaction rate The speed of a reaction.

recombinant DNA DNA of an organism that contains genetic material from another organism.

reducing agent The substance that contains an element that is oxidized during a chemical reaction.

reducing sugar A sugar that can be oxidized by Cu^{2+} solutions.

reduction Originally, a process in which oxygen was lost. Today it means a number of things, including a process in which electrons are gained, hydrogen is accepted, or an oxidation number decreases.

Reference Daily Intakes (RDIs) A set of standards for protein, vitamins, and minerals used on food labels as part of the Daily Values.

relative specificity The characteristic of an enzyme that it acts on several structurally related substances.

rem A biological unit of radiation measurement corresponding to the health effect produced by 1 roentgen of gamma or X-rays, regardless of the type of radiation involved.

renal threshold The blood glucose level at which glucose begins to be excreted in the urine.

replication The process by which an exact copy of a DNA molecule is produced.

replication fork A point where the double helix of a DNA molecule unwinds during replication.

representative element An element in which the distinguishing electron is found in an *s* or a *p* subshell.

respiratory acidosis A condition of acidosis caused by hypoventilation.

respiratory alkalosis A condition of alkalosis caused by hyperventilation.

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

restriction enzyme A protective enzyme found in some bacteria that catalyzes the cleaving of all but a few specific types of DNA.

ribonucleic acid (RNA) A nucleic acid found mainly in the cytoplasm of cells.

ribosomal RNA (rRNA) RNA that constitutes about 65% of the material in ribosomes, the sites of protein synthesis.

ribosome A subcellular particle that serves as the site of protein synthesis in all organisms.

roentgen A biological unit of radiation measurement used with X-rays and gamma rays; the quantity of radiation that generates 2.1×10^9 ion pairs per 1 cm^3 of dry air or 1.8×10^{12} ion pairs per 1 g of tissue.

salt A solid crystalline ionic compound at room temperature that contains the cation of a base and the anion of an acid.

saponification The basic cleavage of an ester linkage.

satiety A state of satisfaction or fullness.

saturated hydrocarbon Another name for an alkane.

saturated solution A solution that contains the maximum amount possible of dissolved solute in a stable situation under the prevailing conditions of temperature and pressure.

scientific models Explanations for observed behavior in nature.

scientific notation A way of representing numbers consisting of a product between a nonexponential number and 10 raised to a whole-number exponent that may be positive or negative.

scintillation counter A radiation-detection device operating on the principle that phosphors give off light when struck by radiation.

secondary alcohol An alcohol in which the carbon bearing the OH group is attached to two other carbon atoms.

secondary amine An amine having two alkyl or aromatic groups bonded to nitrogen, as in R_2NH.

secondary protein structure The arrangement of protein chains into patterns as a result of hydrogen bonds between amide groups of amino acid residues in the chain. The common secondary structures are the α-helix and the β-pleated sheet.

semiconservative replication A replication process that produces DNA molecules containing one strand from the parent and a new strand that is complementary to the strand from the parent.

shape Shape depends on the physical state of matter.

shell A location and energy of electrons around a nucleus that is designated by a value for n, where $n = 1, 2, 3$, etc.

side reactions Reactions that do not give the desired product of a reaction.

significant figures The numbers in a measurement that represent the certainty of the measurement, plus one number representing an estimate.

simple carbohydrates Monosaccharides and disaccharides, commonly called sugars.

simple ion An atom that has acquired a net positive or negative charge by losing or gaining electrons.

simple lipid An ester-containing lipid with just two types of components: an alcohol and one or more fatty acids.

simple protein A protein made up entirely of amino acid residues.

single-replacement reaction A chemical reaction in which an element reacts with a compound and displaces another element from the compound.

soap A salt of a fatty acid often used as a cleaning agent.

solubility The maximum amount of solute that can be dissolved in a specific amount of solvent under specific conditions of temperature and pressure.

soluble substance A substance that dissolves to a significant extent in a solvent.

solute One or more substances present in a solution in amounts less than that of the solvent.

solutions Homogenous mixtures of two or more pure substances.

solvent The substance present in a solution in the largest amount.

specific heat The amount of heat energy required to raise the temperature of exactly 1 g of a substance by exactly 1°C.

spectator ions The ions in a total ionic reaction that are not changed as the reaction proceeds. They appear in identical forms on the left and right sides of the equation.

sphingolipid A complex lipid containing the aminoalcohol sphingosine.

spontaneous process A process that takes place naturally with no apparent cause or stimulus.

stable substance A substance that does not undergo spontaneous changes under the surrounding conditions.

standard atmosphere The pressure needed to support a 760-mm column of mercury in a barometer tube.

standard boiling point See **normal boiling point**.

standard conditions (STP) A set of specific temperature and pressure values used for gas measurements.

standard position for a decimal In scientific notation, the position to the right of the first nonzero digit in the nonexponential number.

state of equilibrium A condition in a reaction system when the rates of the forward and reverse reactions are equal.

stereochemical specificity The characteristic of an enzyme that it is able to distinguish between stereoisomers.

stereoisomers Compounds with the same structural formula but different spatial arrangements of atoms.

steroid A compound containing four rings fused in a particular pattern.

stoichiometry The study of mass relationships in chemical reactions.

strong acids and strong bases Acids and bases that dissociate (ionize) completely when dissolved to form a solution.

structural isomers Compounds that have the same molecular formula but in which the atoms bond in different patterns.

sublimation The endothermic process in which a solid is changed directly to a gas without first becoming a liquid.

subshell A component of a shell that is designated by a letter from the group *s, p, d,* and *f.*

substrate The substance that undergoes a chemical change catalyzed by an enzyme.

subunit A polypeptide chain having primary, secondary, and tertiary structural features that is a part of a larger protein.

sulfhydryl group The —SH functional group.

supercritical mass The minimum amount of fissionable material that must be present to cause a branching chain reaction to occur.

supercritical reaction A branching chain reaction.

supersaturated solution An unstable solution that contains an amount of solute greater than the solute solubility under the prevailing conditions of temperature and pressure.

surface catalyst See **heterogeneous catalyst**.

tertiary alcohol An alcohol in which the carbon bearing the OH group is attached to three other carbon atoms.

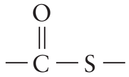
tertiary amine An amine having three alkyl or aromatic groups bonded to nitrogen, as in R_3N.

tertiary protein structure A specific three-dimensional shape of a protein resulting from interactions between R groups of the amino acid residues in the protein.

thermal expansion The change in volume of a sample resulting from a change in temperature of the sample.

thermonuclear reaction A nuclear fusion reaction that requires a very high temperature to start.

thioester bond The carbon–sulfur bond of the



$-\overset{\overset{O}{\|}}{C}-S-$ functional group.

thiol A compound containing an —SH group.

titration An analytical procedure in which one solution (often a base) of known concentration is slowly added to a measured volume of an unknown solution (often an acid). The volume of the added solution is measured with a buret.

Tollens' reagent A mild oxidizing solution containing silver ions used to test for aldehydes.

torr The pressure needed to support a 1-mm column of mercury in a barometer tube.

total ionic equation An equation written with all soluble ionic substances represented by the ions they form in solution.

trace mineral A mineral found in the body in quantities smaller than 5 g.

tracer A radioisotope used medically because its progress through the body or localization in specific organs can be followed.

trans- On opposite sides (as applied to *cis-trans* isomers).

transaminase An enzyme that catalyzes the transfer of an amino group.

transamination The enzyme-catalyzed transfer of an amino group to a keto acid.

transcription The transfer of genetic information from a DNA molecule to a molecule of messenger RNA.

transfer RNA (tRNA) RNA that delivers individual amino acid molecules to the site of protein synthesis.

transition element An element in which the distinguishing electron is found in a *d* subshell.

translation The conversion of the code carried by messenger RNA into an amino acid sequence of a protein.

transuranium elements Synthetic elements with atomic numbers greater than that of uranium.

triatomic molecules Molecules that contain three atoms.

triglyceride (triacylglycerol) A triester of glycerol in which all three alcohol groups are esterified.

triple bond The bond resulting from the sharing of three pairs of electrons.

triprotic acid An acid that gives up three protons (H^+) per molecule when dissolved.

turnover number The number of molecules of substrate acted on by one molecule of enzyme per minute.

Tyndall effect A property of colloids in which the path of a beam of light through the colloid is visible because the light is scattered.

universal gas constant The constant that relates pressure, volume, temperature, and number of moles of gas in the ideal gas law.

unsaturated hydrocarbon A hydrocarbon containing one or more multiple bonds.

urea cycle A metabolic pathway in which ammonium ions are converted to urea.

valence shell The outermost (highest-energy) shell of an element that contains electrons.

vaporization See **evaporation**.

vapor pressure The pressure exerted by vapor that is in equilibrium with its liquid.

vector A carrier of foreign DNA into a cell.

vitamin An organic nutrient that the body cannot produce in the small amounts needed for good health.

volume/volume percent A concentration that expresses the volume of liquid solute contained in 100 volumes of solution.

VSEPR theory A theory based on the mutual repulsion of electron pairs. It is used to predict molecular shapes.

water of hydration Water retained as part of the solid crystalline structure of some salts.

wax An ester of a long-chain fatty acid and a long-chain alcohol.

weak (or moderately weak) acids and bases Acids and bases that dissociate (ionize) less than completely when dissolved to form a solution.

weight A measurement of the gravitational force acting on an object.

weight/volume percent A concentration that expresses the grams of solute contained in 100 mL of solution.

weight/weight percent A concentration that expresses the mass of solute contained in 100 mass units of solution.

zwitterion A dipolar ion that carries both a positive and a negative charge as a result of an internal acid–base reaction in an amino acid molecule.

zymogen or proenzyme The inactive precursor of an enzyme.

INDEX

A
A site, 693*f*, 694, 694*f*
Abbreviated electronic configurations, 82, 99
Absolute specificity, 648
Absolute zero, 173
Acesulfame-K, 561
Acetal, 457, 461
Acetaldehyde, 338*t*, 449*t*
Acetamide, 338*t*, 528
Acetaminophen, 522
Acetic acid
  characteristics and primary uses, 480*t*
  functional group, 338*t*
  K_a and pK_a values, 291*t*
  molarity, 271*t*
  monoprotic, 282
  name, 479, 485, 528
  physical properties, 481*t*
  vinegar, 270*f*, 479*f*
  weak acid, 281*t*
Acetoacetate, 771, 772*f*
Acetone, 338*t*, 448*f*, 449*t*, 451*t*, 464, 464*f*
Acetone breath, 772
Acetyl CoA. *See* Acetyl coenzyme A (acetyl CoA)
Acetyl coenzyme A (acetyl CoA), 718, 719*f*, 741, 768, 768*f*, 771, 774
Acetylcholine, 518, 775
Acetylene, 338*t*, 373, 390*f*
ACGT, 677*f*
Acid-base balance, 801
Acid-base imbalance, 803–805
Acid-base titration, 285–288
Acid dissociation constant, 281, 282, 294
Acid phosphatase, 663*t*
Acid reflux disease, 284
Acid solution, 266
Acidosis, 773, 801, 804, 805, 805*t*
Acids, bases, and salts, 260–302
  acid dissociation constant, 281, 282, 294
  analyzing acids and bases, 285–288
  Arrhenius theory, 261
  Brønsted theory, 261–263
  buffers, 289–292
  common laboratory acids and bases, 271*t*
  compound preparation equations, 278
  conjugate base/conjugate acid-base pair, 262
  dissociation reaction of acids, 282
  general reactions of acids, 278, 294
  Henderson-Hasselbalch equation, 290, 291
  hydrolysis reactions of salts, 288–289
  loss of protons, 282
  monoprotic, diprotic, and triprotic acids, 282, 283*t*
  naming acids, 263–265
  pH concept, 267–271
  properties of acids, 271–275
  properties of bases, 275
  salts, 276–280
  self-ionization of water, 265–267
  solution classifications and calculations, 266–267
  strength of acids and bases, 281–285
  strong acids and bases, 281, 281*t*
  titration, 285–288
  weak acids and bases, 281, 281*t*
  writing reactions of acids, 276
cis-aconitate, 416
ACP. *See* Acyl carrier protein (ACP)
Acrilan, 389*t*
ACTH. *See* Adrenocorticotropic hormone (ACTH)
Activation energy, 240, 243*f*, 245*f*, 251*f*
Activator, 661
Active site, 651
Activity series, 274, 274*t*
Actual mass, 57
Actual yield, 155
Acute radiation syndrome, 311
Acyl carrier protein (ACP), 774
Acyl CoA, 767–769
Acyl CoA synthetase, 767
Added sugars, 710
Addition polymers, 386–390
Addition reaction, 146, 380–383
Adenine, 674, 674*f*
Adenosine diphosphate (ADP), 498, 499
  citric acid cycle, 745
  glycolysis, 740
  hydrolysis of ATP, 720
  oxidative phosphorylation, 747–749
Adenosine monophosphate (AMP), 721, 740
Adenosine triphosphate (ATP), 498, 499
  ATP-ADP cycle, 723, 723*f*
  calculating ATP production, 771
  chemical processes, 767
  chemiosmotic hypothesis, 747, 748*f*
  citric acid cycle, 745
  complete oxidation of glucose, 749–750
  glycolysis, 740
  hydrolysis, 721–723
  key number for ATP calculations, 752, 773
  mitochondria, 723, 724*f*
  oxidative phosphorylation, 747–749
  structure, 720, 720*f*
  total ATP from 18-carbon fatty acid, 770*t*
ADH. *See* Antidiuretic hormone (ADH)
Adipose tissue, 766
ADP. *See* Adenosine diphosphate (ADP)
Adrenal cortex, 604
Adrenal glands, 604
Adrenaline, 525
Adrenocorticoid hormones, 604–605
Adrenocorticotropic hormone (ACTH), 624, 625*t*
Advantame, 561
Advil, 522
Aerobic, 741
Aftershave lotions, 425*f*
Aircraft de-icers, 411*f*
Alanine, 617*t*, 691*t*, 783*t*
Alanine transaminase (ALT), 663*t*
D-alanine, 553
L-alanine, 553
Alanylglycine, 622, 623
Alanylglycylvaline, 623
Albuminuria, 799*t*
Alcohol dehydrogenase, 649
Alcoholic drinks, 225
Alcoholic fermentation, 742
Alcohols
  “alcohol,” 410*f*
  aldehydes and ketones, 456–463
  alkenes, 415–417
  antidepressants, 424
  boiling point, 415, 415*f*, 482*t*
  classification, 412–413
  defined, 409
  dehydration reaction, 415–418
  ethers, 417–418
  functional group, 338*t*
  hydrogen bonding, 414, 414*f*, 415, 415*f*
  multistep reactions, 421–422
  naming, 410–412
  oxidation reaction, 418–421
  physical properties, 413–415, 451*t*
  primary, secondary, tertiary, 412, 413*t*
  reaction map, 423
  reactions, 415–422
  solubility, 414
  structural formula, 338*t*
  uses of specific alcohols, 422–425
Aldehydes and ketones, 446–476
  acetone, 464, 464*f*
  addition of alcohols, 456–463
  addition of hydrogen, 455–456
  aldehyde/ketone, defined, 447
  Benedict’s reagent, 455, 455*f*
  boiling points, 451–452, 451*t*, 452*f*, 482*t*
  chemical properties, 452–463, 466
  common aldehydes/ketones, 449*t*
  difference in reactivity toward oxidation, 453, 453*f*
  formaldehyde, 464
  fragrant odors (flavoring), 464, 464*f*, 465*t*
  functional group, 338*t*
  hemiacetals, 456, 457, 459, 460
  hemiketals/ketals, 457, 459, 460
  hydrogenation reactions, 456
  hydrolysis/hydrolysis reactions, 461, 462
  naming aldehydes, 448–449
  naming ketones, 450
  oxidation reactions, 452–455
  physical properties, 450–452, 466
  reaction map, 460
  sex hormones, 464
  Tollens’ reagent, 454, 455
  water solubility, 451*t*, 452
Aldohexose, 556, 557*f*
Aldopentose, 557*f*
Aldose, 556
D-aldoses, 557*f*
Aldosterone, 605, 800, 801
Aldotetrose, 557*f*
Aldotriose, 557*f*
Aleve, 522
Aliphatic compound, 392, 482
Alkaline phosphatase (ALP), 655*t*, 663*t*
Alkaline solution, 266
Alkaloids, 526–527
Alkalosis, 801, 804, 805, 805*t*
Alkanes, 339*f*
  boiling point, 357, 358*f*, 482*t*
  classifying alkane chains, 342–343
  combustion reactions, 359–361
  conformations, 343–344
  cycloalkanes. *See* Cycloalkanes
  defined, 339
  emollients, 359
  functional group, 338*t*
  general formula, 339
  longest chains, 347–349
  moisturizers, 357
  molecular formulas, 342*t*
  nomenclature, 345–352
  normal/branched, 342
  physical properties, 357–359, 451*t*
  plants, 358*f*
  possible structural isomers, 342*t*
  structural formula, 338*t*
Alkenes, 339*f*
  addition polymers, 386–390
  addition reactions, 380–383
  alcohols, 415–417
  chemical properties, 380–386
  cis-trans isomerism, 377–378, 378*t*, 379
  cis-trans stereoisomerism, 378
  defined, 373
  functional group, 338*t*
  general formula, 374
  halogenation/halogenation reactions, 380, 381–382
  hydration/hydration reactions, 385, 386
  hydrogenation/hydrogenation reactions, 382, 382–383
  IUPAC names, 373–375
  Markovnikov’s rule, 383–386
  physical properties, 380, 380*t*
  reaction map, 388
  simplest members, 374
  structural formula, 338*t*
Alkoxy group, 428
Alkyl groups
  defined, 346
  name, 346, 349–350
  nomenclature of amides, 529
  overview, 347*t*
Alkyl halide, 380, 383
Alkynes, 338*t*, 339*f*, 373, 390–391
Allergy/immunology nurse, 510, 534–535
Allosteric enzyme, 661
Allosteric regulation, 661
Allotropes, 127
Almonds, 765
ALP. *See* Alkaline phosphatase (ALP)
Alpha-amino acid, 615–616. *See also* Amino acids
α-helix, 630, 630*f*, 631*f*
Alpha particles, 306, 319
Alpha radiation, 306
Alpha rays, 305, 305*f*, 306*t*
ALT. *See* Alanine transaminase (ALT)
American Board of Cardiovascular Perfusion (ABCP), 806
American Cancer Society, 34
American Dental Association, 572
American Heart Association, 174
American Medical Association, 34
Americium-241, 306*f*
Amide hydrolysis, 532, 533
Amide linkage, 519
Amides
  amines, and, 519–522
  defined, 519
  functional group, 338*t*
  hydrogen bonding, 530–531
  hydrolysis/hydrolysis reactions, 532, 533

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Amides (*Continued*)
  medical uses, 534*t*
  neutrality, 532
  nomenclature, 528–530
  physical properties, 530–531
  polyamides, 521–522
  structural formula, 338*t*
Amine salts, 516–519
Amines
  alkaloids, 526–527
  amide formation, 519–522
  amphetamines, 526
  anilines, 513
  basicity, 516
  boiling points, 514
  chemical properties, 515–522
  classifying, 511–512
  defined, 511
  derivatives of ammonia, 516
  epinephrine (adrenaline), 525
  functional group, 338*t*
  hydrogen bonding, 514, 515
  neurotransmitters, 522–525
  nomenclature, 512–513
  odor, 515
  physical properties, 514–515
  quaternary ammonium salts, 518–519, 519*f*
  reaction map, 525
  salts, 516–519
  structural formula, 338*t*
  water solubility, 514
Amino acid biosynthesis, 783–784
Amino acid catabolism
  carbon skeleton, 780–782
  nitrogen atoms, 776–779
Amino acid metabolism, 774–775
Amino acid pool, 774
Amino acid residue, 623
Amino acids. *See also* Proteins
  amino acid residue, 623
  biosynthesis, 783–784
  catabolism (carbon skeleton), 780–782
  catabolism (nitrogen atoms), 776–779
  common amino acids of proteins, 617*t*
  compounds derived from, 775*t*
  deamination, 777–778
  essential, 711, 711*t*, 783*t*
  functions, 763
  glucogenic, 780*f*, 781
  isoelectric point, 619
  ketogenic, 780*f*, 781
  major metabolic pathways, 775*f*
  N-terminal residue/C-terminal residue, 623
  nonessential, 783, 783*t*
  oxidation of cysteine, 620
  peptides, 621–625
  prosthetic groups, 627
  R groups (side chains), 615, 616, 617*t*, 628, 630
  stereochemistry, 618
  structure, 615–616
  three-letter/one-letter abbreviation, 617*t*
  transamination, 776–777
  zwitterions, 618–620
Amino group, 347*t*
p-aminobenzoic acid, 658*f*
Ammonia, 284, 516
Ammonia solutions, 263*f*
Ammonium chloride, 240*f*, 289
Ammonium ion, 124, 291*t*
Amobarbital, 534*t*
AMP. *See* Adenosine monophosphate (AMP)
Amphetamine, 526
Amphetamines, 526
Ampicillin, 534*t*, 657*t*
Amylase, 663*t*
Amylopectin, 569, 569*f*, 570*f*, 709
Amylose, 568, 568*f*, 709
Amytal, 534*t*
Anabolic steroids, 605
Anabolism, 718
Anacin-3, 522
Anaerobic, 741
Anaprox, 522
Anesthesiologist assistant, 372, 398
Anesthetics, 430
Angina pectoris, 498
Angiotensin II, 625*t*
Anhydrous compound name, 264
Aniline, 394, 397*t*, 513
Animal fats, 589. *See also* Fats and oils
Anion, 276
Anomer, 559
Anomeric carbon, 558
Answers to end-of-chapter exercises, B-1 to B-60
Antacid tablets, 141*f*
Antibiotics, 656
Antibodies, 626
Anticodon, 685
Antidepressant medications, 424
Antidiuretic hormone (ADH), 624, 800. *See also* Vasopressin
Antifreeze, 219*f*, 424*f*
Antioxidants, 426–427
Antiseptics, 426
(aq), 139
Apiarist, 330, 361–362
Apoenzyme, 650
Apple cider vinegar, 270*f*
Apples, 479
Aqueous ammonia, 271*t*
Arachidic acid, 586*t*
Arachidonic acid, 586*t*
Area, 14
Arginase, 655*t*
Arginine, 617*t*, 691*t*, 783*t*
Argon-40, 318
Aromatic amines, 513
Aromatic compounds, 339*f*, 391–397
  defined, 373
  functional group, 338*t*
  important, 397*t*
  Kekulé structures, 392, 393
  major sources, 397
  nomenclature of benzene derivatives, 393–396, 399
  nutrition, 397
  polycyclic, 396–397
  properties, 396
  structural formula, 338*t*
  uses, 397
Aromatic hydrocarbons, 373. *See also* Aromatic compounds
Aromatics. *See* Aromatic compounds
Arrhenius, Svante, 261
Arrhenius acid, 261
Arrhenius base, 261
Arrhenius theory, 261
Arsenic, 715*t*
Artificially induced nuclear reactions, 318–321
Ascorbic acid, 713*t*
Asparagine, 616, 617*t*, 691*t*, 783*t*, 784
Aspartame, 561, 782
Aspartate, 617*t*, 783*t*
Aspartate transaminase (AST), 663*t*
Aspartic acid, 691*t*
Aspirin, 495
Aspirin substitutes, 522
AST. *See* Aspartate transaminase (AST)
Astatine, 320
Athlete's foot, 486
Atom
  atomic mass unit, 53
  atomic number, 51
  atomic weight, 53
  central, 114
  defined, 9
  electronic arrangements, 73–75
  isotopes, 51, 55–56
  mass, 50
  mass number, 51
  metal atom, metal ion, noble gas atom, compared, 101*t*
  nucleus, 50
  relative mass, 52–54
  scale drawings, 88*f*
  size, 88
  subatomic particles, 50, 50*t*
  valence shell relationship, 77
Atomic bombs, 323, 323*f*
Atomic Lewis structure, 109*t*
Atomic mass unit, 53
Atomic number, 51
Atomic orbital
  defined, 73
  fourth shell of an atom, 75*f*
  hybrid orbital, 334, 335*f*
  isomerism, 335
  molecular orbital, 108
  s, p, and *d* orbitals, 74, 74*f*
  shapes of orbitals, 74, 74*f*
  shells, subshells, and electrons, relationship with, 75*t*
Atomic orbital overlap, 108, 108*f*
Atomic pile, 322
Atomic weight, 53, 56, 57
ATP. *See* Adenosine triphosphate (ATP)
ATP-ADP cycle, 723, 723*f*
Atropine, 527
Autoclave, 185, 636*f*
Automobile safety glass, 388*f*
Automobiles, 153–154
Automotive antifreeze, 219*f*, 424*f*
Average mass, 56
Avian field technician, 672, 699
Avogadro, Amadeo, 178
Avogadro's law, 178
Avogadro's number, 59
Axon, 523, 523*f*

B

Bacon, 650
Bactine, 519
Bakelite, 397, 397*t*, 464
Balanced equation, 139, 140–141
Balanced nuclear equations, 307–309
Ball-and-stick model, 336*f*, 341*f*, 355*f*, 448*f*
Basic solution, 266
Basic unit of measurement, 14
Becquerel (Bq), 313, 314*t*
Becquerel, Henri, 305
Beekeeper, 330, 361–362
Beer, 410*f*
Beeswax, 361, 594*f*
Belladonna plant, 526
Bends (decompression sickness), 203
Benedict's reagent, 455, 455*f*, 561, 567*f*
Benzaldehyde, 449*t*
Benzalkonium chloride, 519
Benzamide, 528
Benzedrine, 526
Benzene, 338*t*, 373, 392, 397*t*. *See also* Aromatic compounds
Benzene derivatives, 393–396, 399
Benzoic acid, 394, 528
Benzopyrene, 396
2-benzyl-4-chlorophenol, 426
Beta blockers, 524
Beta particles, 306, 308
β-pleated sheet, 631, 631*f*
Beta rays, 305, 305*f*, 306*t*
BHA (butylated hydroxy anisole), 426, 427
BHT (butylated hydroxy toluene), 426, 426*f*, 427
Biacetyl, 465*t*
Biblical cubit, 13, 13*f*
Bicarbonate buffer system, 801
Bicarbonate ion, 291*t*, 801, 803, 804*f*
Bile, 602
Bile salts, 603
Binary compound, 102
Biochemistry, 547
Biological membranes, 600–602
Biological unit of radiation, 313
Biomolecule, 547, 565
Bioprocesses, 722
Biotin, 651*t*, 713*t*
Bisulfite ion, 291*t*
Blood acid-base imbalance, 803–805
Blood buffer, 290*f*
Blood glucose, 737–738, 738*f*
Blood lipids, 763–766
Blood plasma, 793, 793*f*
Blood pressure reading, 174
Blood sugar, 564. *See also* Glucose
Blood sugar level, 737–738, 740
Boat form, 354, 355*f*
Body. *See* Human body
Body fluids, 792–810
  acid-base balance, 801
  acid-base imbalance, 803–805
  acidosis and alkalosis, 803–805
  buffer control of blood pH, 801–802
  chemical transport to the cells, 797–798
  distribution of, 793*f*
  fluid and electrolyte balance, 799–801
  interstitial fluid, intracellular fluid, and plasma, 793, 794*f*
  oxygen and carbon dioxide transport, 794–797
  respiratory control of blood pH, 802
  urinary control of blood pH, 802–803
  urine, 798, 799, 799*t*
Body temperature, 19
Bohr, Niels, 73
Bohr hydrogen atom, 73*f*
Bohr model, 73
Boil water notice, 186
Boiling, 184, 184*f*
Boiling point
  alcohols, 415, 415*f*
  aldehydes and ketones, 451–452, 451*t*, 452*f*
  alkanes, 357, 358*f*
  amines, 514
  defined, 184
  elevation (altitude), 185*f*
  lattice particles, 125
  normal, 184
  periodic table, 129
  pressure cooker, 185, 185*t*
  solutions, 219–221
Bombardment of nuclei, 319–320, 326
Bond polarization, 118
Bones, 54
Bonneville Salt Flats, 277*f*
Borax, 277*t*
Boric acid, 281*t*, 291*t*
Botulism, 637
Boyle, Robert, 174
Boyle's law, 175
Branched alkane, 342
Branching chain reaction, 321
Breathalyzer test, 418*f*
Breeder reaction, 323
Breeder reactors, 324–325
Breeding reactions, 324
Brick wall analogy, 378
Bromination, 380–381
Bromine, 87*f*
Bromo group, 347*t*
1-bromo-3-chlorobenzene, 395
Bromobenzene, 394
3-bromobutanoic acid, 481
3-bromobutanal, 448
m-bromochlorobenzene, 395
4-bromophenol, 412
1-bromopropane, 383
2-bromopropane, 383
Brønsted, Johannes, 262

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

- Brønsted acid, 262
- Brønsted acid-base behavior, 283
- Brønsted base, 262, 516
- Brønsted theory, 261–263
- Bubble gum, 388*f*
- Buffer, 289–292
- Buffer capacity, 290
- Buffer control of blood pH, 801–802
- Buffer system, 290, 801–802
- Buried zeros, 24, 24*f*
- 1,3-butadiene, 375
- Butanal, 449*t*, 482*t*
- Butane, 341, 345*t*, 358*t*, 374, 451*t*
- Butanedione, 450*f*
- *n*-butane, 342*f*, 343*f*, 344*f*, 345, 346, 347*t*
- Butanoic acid, 480*t*
- Butanol, 425*t*
- 1-butanol, 425*t*, 482*t*
- 2-butanol, 385
- Butanone, 449*t*
- Butene, 374
- 1-butene, 380*t*, 381
- 2-butene, 374, 385
- *cis*-2-butene, 377, 378, 378*t*
- *trans*-2-butene, 377, 378, 378*t*
- *trans*-2-butene-1-thiol, 431
- Butterfat, 588
- Butyl group, 347*t*
- *sec*-butyl group, 347*t*
- *t*-butyl alcohol, 413
- *t*-butyl group, 347*t*
- 2-*t*-butyl-4-methoxphenol, 427
- Butylated hydroxy anisole (BHA), 426, 427
- Butylated hydroxy toluene (BHT), 426, 426*f*, 427
- 1-butyne, 391
- Butyraldehyde, 449*t*
- Butyric acid, 283*t*, 479, 480*t*, 481, 481*t*, 529

C

- C-terminal residue, 623
- Caffeine, 526, 527
- Calciferol, 713*t*
- Calcium, 715*t*, 716*f*
  - bone health, 54
  - member of group IIA(2), 76*f*
- Calculations. *See* Measurements, calculations, and numbers
- Calculator
  - calculating pH from molarity, 270
  - scientific notation calculations, 22*t*
  - too few/too many figures, 25*f*
- Californium, 320
- calorie (cal), 18
- Calorie (Cal), 18
- Camphor, 465*t*
- Cancer-producing compounds, 396–397
- Candles, 481, 594, 594*f*
- Candy, 487
- Cane sugar, 447
- Canister stove, 347*f*
- Cannabist industry, 190
- Capric acid, 481*t*
- Caproic acid, 480*t*, 481*t*
- Caprylic acid, 481*t*
- Capsaicin, 463
- Capzasin-P, 463
- Carbaminohemoglobin, 795, 796
- Carbohydrate digestion, 737
- Carbohydrate metabolism, 736–761. *See also* Carbohydrates
  - blood glucose, 737–738, 738*f*
  - chemiosmotic hypothesis, 747, 748*f*
  - citric acid cycle, 743–746
  - complete oxidation of glucose, 749–750
  - Cori cycle, 753, 753*f*
  - digestion of carbohydrates, 737
  - electron transport chain, 746–747, 747*f*
  - fates of pyruvate, 741–742
  - gluconeogenesis, 753, 754*f*
  - glycogen metabolism, 751–752
  - glycogenesis, 751
  - glycogenolysis, 751–752
  - glycolysis, 738–740
  - hormonal control, 754–755, 755*t*
  - oxidative phosphorylation, 746–747, 747*f*
- Carbohydrates, 546–580, 709–710
  - chiral carbon, 549–552
  - classes, 547–548
  - defined, 548
  - disaccharides, 564–568
  - enantiomers, 548, 548*f*
  - Fischer projections, 552–553, 557*f*
  - functional groups, 547
  - functions, 547
  - L and D compounds, 552–556
  - metabolism. *see* Carbohydrate metabolism
  - monosaccharides. *see* Monosaccharides
  - polysaccharides, 568–572
  - simple/complex, 709
  - stereochemistry, 548–552
  - stereoisomers, 552
- Carbolic acid, 425
- Carbon
  - anomeric, 558
  - atomic weight, 57, 57*f*
  - bonding characteristics, 334
  - building block of all cells in body, 58*f*
  - chiral, 549–552
  - element of organic compounds, 331–332
  - recycling of Earth's carbon compounds (carbon cycle), 717, 718*f*
  - *sp*^{2} hybridization, 377*f*
- Carbon-12, 53
- Carbon-14, 317, 318
- Carbon compounds, 107*f*
- Carbon cycle, 717, 718*f*
- Carbon dioxide
  - covalent bonding, 109*t*
  - factor-unit calculations, 60–61
  - greenhouse gas, 227
  - initial source of carbon for carbohydrates, 717, 717*f*
  - minimally invasive surgery, 115
  - numerical data related to gaseous state, 171*t*
  - oceans, 263
  - relative mass, 60
  - sublimation, 185
  - transport within bloodstream, 794–797
- Carbon disulfide, 61*f*
- Carbon footprint, 359
- Carbon monoxide
  - behavior, in response to heating, 126*t*
  - harmful when breathed, 119
- Carbon monoxide detectors, 360
- Carbon monoxide molecules, 8, 11, 48
- Carbon tetrachloride, 127
- Carbonated beverages, 203*f*
- Carbonic acid
  - blood pH, 801–803, 804*f*
  - buffer system, 290
  - carbon dioxide dissolving in water, 263
  - diprotic acid, 283*t*
  - isolation in the pure state, 277
  - K_a and pK_a values, 291*t*
  - weak acid, 281*t*
- Carbonic anhydrase, 653*t*
- Carbonyl group, 447, 464
- Carboxyl group, 468, 479
- Carboxylate ion, 483
- Carboxylic acid. *See also* Carboxylic acids and esters
  - acidity, 483–485
  - amine salts, 517
  - boiling point, 482*t*
  - carboxylic esters, 487–492
  - defined, 479
  - examples, 480*t*
  - functional group, 338*t*
  - nomenclature, 479–481
  - physical properties, 481–483
  - reaction map, 496
  - salts, 485–487
  - structural formula, 338*t*
- Carboxylic acid anhydrides, 490
- Carboxylic acid chlorides, 490
- Carboxylic acid salts, 485–487
- Carboxylic acids and esters, 478–508
  - carboxylic acid. *see* Carboxylic acid
  - carboxylic acid anhydrides, 490
  - carboxylic acid chlorides, 490
  - carboxylic esters, 487–492
  - esters. *see* Esters
- Carboxylic esters, 487–492
- Carboxypeptidase, 660*t*
- Careers. *See* Health and environmental careers
- β-carotene, 375*f*
- Carson, Rachel, 381*f*
- Carvone, 555*f*
- Casein, 626
- CASPA (Centralized Application Service for Physician Assistants), 252
- CAT scan. *See* Computed tomography (CT scan)
- Catabolism, 718
- Catabolism of food, 718–719
- Catalase, 653*t*, 655*t*
- Catalyst, 245, 251*f*
- Cation, 276
- Cauliflower, 712*f*
- CDC. *See* Centers for Disease Control and Prevention (CDC)
- Ceepryn, 519
- Cell membranes, 600–602
- Cellobiose, 566
- Cellular respiration, 717
- Cellulose, 570–572, 709
- Celsius temperature scale, 16, 17*f*
- Centers for Disease Control and Prevention (CDC), 34
- centi-, 14*t*
- Centigrade scale, 16
- Central atom, 114
- Central dogma of molecular biology, 687
- Centralized Application Service for Physician Assistants (CASPA), 252
- Cephalin, 596
- Cereal, 100*f*
- Cerebrosides, 598, 600*t*
- Certified Registered Central Service Technician (CRCST) exam, 35
- CFCs. *See* Chlorofluorocarbons (CFCs)
- Chain elongation process, 694
- Chain reaction, 321–322, 322*f*
- Chair form, 354, 355*f*
- Charles, Jacques, 175
- Charles' law, 175
- Charpentier, Emmanuelle, 697
- Cheese, 223
- Chelating agent, 656
- Chemical changes, 4, 6*f*, 9
- Chemical elements and their symbols, 48*t*
- Chemical equilibrium, 246–247
- Chemical formula, 61
- Chemical properties, 4
- Chemical reaction equations, 139–141, 149
- Chemical reactions, 138–163
  - chemical equations, 139–141
  - classification, 141*f*
  - combination reaction, 146
  - decomposition reaction, 145, 145*f*
  - double-replacement reaction, 147, 147*f*
  - energy and reactions, 150
  - exothermic/endothermic reaction, 150
  - ionic equations, 148–149
  - limiting reactant, 153–155
  - mole and chemical equations, 150–153
  - nonredox reactions, 141, 141*f*
  - percentage yield, 155–156
  - reactants/products, 139
  - redox reactions, 141–145
  - replacement reaction, 146–148
  - side reaction, 155
  - single-replacement reaction, 146–147, 147*f*
  - stoichiometry, 151
  - types of reactions, 141
  - writing reaction equations, 149
- Chemiosmotic hypothesis, 747, 748*f*
- Chemistry
  - central science, as, 5
  - inorganic, 332
  - organic. *see* Organic chemistry
- Chemistry for Though questions
  - acids, bases, and salts, 302
  - alcohols, 444–445
  - aldehydes, 476
  - amines and amides, 543–544
  - atomic weight, 68
  - Avogadro's number, 69
  - body fluids, 810
  - breathalyzer, 163
  - carbohydrate metabolism, 761
  - carbohydrates, 579–580
  - carboxylic acids and esters, 507–508
  - chemical reactions, 163
  - colored compounds, 136–137
  - DNA, 705
  - enzymes, 670
  - equilibrium, 258
  - flashlight battery, 163
  - genetic engineering, 705
  - ketones, 476
  - lipid and amino acid metabolism, 791
  - lipids, 613
  - metal/nonmetal atoms, 137
  - nuclear processes, 329
  - nutrition, 735
  - organic compounds, 371
  - periodic table, 95
  - proteins, 644
  - radioactivity, 329
  - reaction rates, 259
  - solutions and colloids, 235
  - states of matter, 197
  - unsaturated hydrocarbons, 406–407
- Chernobyl nuclear disaster, 324
- Chest rubs, 425*f*
- Children's Tylenol, 487*f*
- Chiral, 549
- Chiral carbon, 549–552
- Chloride compounds, 105*f*
- Chloride shift, 796
- Chlorine, 87*f*, 715*t*, 716*f*
- Chlorine-37, 56
- Chloro group, 347*t*
- 1-chloro-3-methylcyclopentane, 353
- 4-chloro-3,5-dimethylphenol, 426
- Chlorobenzene, 394
- Chlorofluorocarbons (CFCs), 127
- *cis*-1-chloropropene, 379
- *trans*-1-chloropropene, 379
- Chocolate, 528
- Chocolate candies, 595
- Cholesterol, 409, 433, 602
- Choline, 518, 595, 775
- Cholinesterase, 653*t*

ChooseMyPlate.gov, 708*f*
Chromium, 715*t*
Chromosome, 680, 681*f*
Chylomicron, 763, 764, 766*f*
Chymotrypsin, 648, 653*t*, 660, 660*t*
Chymotrypsinogen, 660*t*
Cigarette smoke, 397
Cinnamaldehyde, 465*t*
cis-, 356
cis-trans isomer, 356
cis-trans isomerism, 377–378, 378*t*, 379
cis-trans stereoisomerism, 378
Citral, 465*t*
Citrate, 416
Citric acid, 291*t*, 468*f*, 480*t*
Citric acid cycle, 719*f*, 743–746
Citrus fruits, 261*f*, 468*f*
CK. *See* Creatine kinase (CK)
CLA. *See* Conjugated linoleic acid (CLA)
Clinical laboratory technician, 138, 157
Clinical laboratory technologist, 157
Clostridium botulinum, 637
Cobalamin, 713*t*
Cobalt, 715*t*
Cobalt-60, 316
Codeine, 527
Codon, 691, 691*t*
Coenzyme, 650, 651*t*
Coenzyme A, 724–725, 725*f*
Cofactor, 650–651
Coffee, 241
Cohesive forces, 169
Cold spot, 315
Collagen, 626*f*, 627
Colligative properties, 219, 219*t*, 221
Colloidal dispersions, 223
Colloids, 223–226. *See also* Solutions and colloids
Combination reaction, 146
Combined gas law, 175
Combustion, 144, 360
Combustion reactions, 359–361
Common catabolic pathway
  coenzyme A, 724–725, 725*f*
  defined, 719
  extraction of energy from food, 719, 719*f*
  FAD, 727–729
  NAD^+, 725–726
Common cold, 85
Common names, 345
Competitive inhibitor, 656–659
Complementary DNA strands, 679
Complete oxidation of glucose, 749–750
Complete proteins, 711
Complex carbohydrates, 709
Complex lipids, 583
Compound, 11, 12*f*
Compound formula, 48, 49, 49*t*
Compound preparation equations, 278
Compressibility, 166, 167*t*
Computed tomography (CT scan), 314
Concentration, 208
Condensation, 183
Condensation polymer, 521
Condensation polymerization, 489
Condensed structural formula, 337, 338*t*, 339, 351–352, 353*t*
Conductivity of solutions, 218–219, 218*f*
Confined zeros, 24
Conformations, 343–344
Conjugate acid-base pair, 262
Conjugate base, 262
Conjugated linoleic acid (CLA), 632
Conjugated proteins, 627–628, 628*t*
Conservation of energy, law of, 139
Convention hotels analogy, 81
Cooking shortenings, 592, 592*f*
Copolymer, 388
Copper, 715*t*, 716*f*
Corey, Robert, 630
Cori, Gerty and Carl, 753*f*
Cori cycle, 753, 753*f*
Cortisol, 604
Cortisone, 604, 604*f*, 605
Cottonseed oil, 382
Cottrel precipitator, 224
Cough drops, 425*f*
Coulomb (C), A-1
Covalent bond
  classifying, 120
  defined, 108
  nonpolar, 118, 120, 120*f*
  polar, 118, 120, 120*f*
  strength, 129*f*
Covalent bonding, 107–109, 335–336
Cow's milk, 566
CRCST exam. *See* Certified Registered Central Service Technician (CRCST) exam
Creatine kinase (CK), 663, 663*t*
Crick, Francis H. C., 678
Crisco, 592
CRISPR-Cas9 technology, 697
Cristae, 723
Critical mass, 323
Critical reaction, 322, 322*f*
Crowfoot, Dorothy, 712*f*
Cryogenic surgery, 173*f*
Crystal lattice, 106, 106*f*
Crystallization, 202*f*
CT scan. *See* Computed tomography (CT scan)
Cubic centimeters (cm^3), 15
Cubic decimeters (dm^3), 15
Cubic meters (m^3), 15
Cubit, 13, 13*f*
Cupric chloride, 105*f*
Cuprous chloride, 105*f*
Curie (Ci), 313, 314*t*
Curie, Marie, 313*f*, 318, 319*f*
Cyalume light stick glow, 242*f*
Cyanide ion, 655–656
Cyanide poisoning, 656
Cyanocobalamin, 651*t*
Cyclic particle accelerator, 319–320
Cycloalkanes
  ball-and-stick models, 355*f*
  chair form/boat form, 355*f*
  defined, 352
  name, 352, 353–354
  shape, 354–356
  structural formulas and symbols, 353*t*
Cyclobutane, 353*t*, 354, 355*f*
1,3-cyclohexadiene, 375
Cyclohexane, 353*t*, 354, 355*f*
Cyclohexanone, 449*t*
Cyclohexene, 380*t*
Cyclopentane, 353, 353*t*, 355*f*
Cyclopropane, 240, 353*t*, 354, 355*f*
Cyclotron, 319–320, 319*f*
Cysteine, 616, 617*t*, 620, 620*f*, 691*t*, 775*t*, 783*t*
Cytochrome, 747
Cytochrome oxidase, 656
Cytosine, 674, 674*f*

D

d orbital, 74*f*
Dacron, 490
Daffodil bulbs, 526*f*
Daily Reference Values (DRVs), 707
Daily Values (DVs), 707, 708*f*
Dalton, John, 8, 180
Dalton's atomic theory, 8
Dalton's law, 180, 181*f*
Dark chocolate, 528
Daughter nuclei, 307
Deamination, 777–778
deca-, 122*t*
Decane, 345*t*, 358*t*
deci-, 14*t*
Decomposition, 186
Decomposition reaction, 145, 145*f*
Decompression sickness, 173, 203
Deep-sea divers, 203
Dees, 320
DEET, 520
Degeneracy, 692
Dehydration reaction, 415–418
ΔEN. *See* Electronegativity difference (ΔEN)
ΔG, 721, 722
ΔT, 220
Denaturation, 636–637, 638*t*
Dendrites, 523, 523*f*
Density, 32–33
  calculating, 167
  concept summary, 37
  defined, 32
  gases, 171
  liquids, 170
  solids, 169
  states of matter, 167*t*
  volumes, 168
  water density as function of temperature, 128*t*
Dental assistant, 546, 572
Dental cements, 282*f*
Dental hygienist, 572
Dentist-prescribed teeth whitening medications, 152
Deoxyhemoglobin, 794
D-deoxyribose, 674
Deoxyribonucleic acid. *See* DNA
Deoxyribose, 563
β-D-deoxyribose, 563
Derived unit of measurement, 14
Desenex, 486
Detergents, 225–226
Deuteron, 306, 307
Dew, 183*f*
Dextrorotatory, 555
DHA. *See* Dihydroxyacetone (DHA); Docosahexaenoic acid (DHA)
DHA-containing products, 451
di-, 122*t*
2,6-di-*t*-butyl-4-methylphenol, 427
3,3-di-(1-propenyl)disulfide, 431
Diabetes mellitus, 561, 629, 772
Diagnostic Medical Sonography (DMS), 755
Diagnostic radiation, 308*f*, 314
Diagnostic tracers, 315–316, 317, 317*f*
Dialysis, 226–227
Dialyzing membrane, 226
Diamonds, 238*f*
Dianabol. *See* Methandrostenolone (Dianabol)
Diatomic molecules, 8
Diazepam, 534*t*
Dibenzanthracene, 396
1,2-dibromobutane, 381
m-dibromobenzene, 394
o-dibromobenzene, 394
p-dibromobenzene, 394
3,5-dichlorobenzoic acid, 395
Dienes, 433
Diesel fuel, 360
Diester, 497, 498
Diet drinks, 225
Diet foods, 782
  Dietary Guidelines (2015-2020), 709–710, 711
Dietary potassium, 74
Dietary Supplement Health and Education Act (DSHEA), 53
Diethyl ether, 417, 428, 430, 482*t*
N,N-diethylpropanamide, 530
N,N-diethylpropionamide, 530
Diffusion, 181, 189, 221, 221*f*, 793
Digestion, 718, 719*f*
Dihydrogen borate ion, 291*t*
Dihydrogen citrate ion, 291*t*
Dihydrogen phosphate ion, 291*t*
Dihydroxyacetone (DHA), 451
Dihydroxyacetone phosphate, 767
2,6-diisopropylphenol, 412
Dilution, 214–216
Dimer, 482
Dimethyl ether, 336, 336*f*, 338*t*, 428
2,3-dimethyl-1,3,5-hexatriene, 376
4,5-dimethyl-1,3,5-hexatriene, 376
Dimethylamine, 512, 514*t*
N,N-dimethylacetamide, 529
N,N-dimethylaniline, 513
2,4-dimethylbutane, 350
3,3-dimethylbutane, 350
1,1-dimethylcyclobutane, 356
cis-1,2-dimethylcyclobutane, 356
cis-1,3-dimethylcyclobutane, 356
trans-1,2-dimethylcyclobutane, 356
trans-1,3-dimethylcyclobutane, 356
1,2-dimethylcyclopentane, 353
cis-1,2-dimethylcyclopentane, 355*f*
trans-1,2-dimethylcyclopentane, 355*f*
N,N-dimethylethanamide, 529
Diols, 411, 433
Dipeptide, 621
1,1-diphenylcyclobutane, 394
Diphosphates, 498
Dipolar force, 126, 129*f*
Dipole, 121, 128
Dipropyl ether, 428
Diprotic acid, 282, 283*t*
Disaccharides, 548*f*
  defined, 548
  identifying disaccharide linkages, 566
  lactose, 565–566, 568*t*
  maltose, 564–565, 568*t*
  polysaccharides, compared, 568*t*
  sucrose, 567, 568*t*
Disease/illness. *See* Human health
Disinfectants, 519
Dispersed phase, 223, 224*t*
Dispersing medium, 223, 224*t*
Dispersion forces, 128, 129, 129*f*
Disruptive forces, 169
Dissociation constant for acids, 281, 282, 294
Dissociation reaction of acids, 282
Dissolving, 199
Dissolving rate, 207
Distinguishing electron, 83
Disulfide, 431–432
Disulfide bridge, 624, 632, 633*f*
Disulfide linkages, 432
Divinyl ether, 430
DNA
  base sequences, 680
  checkup, 690
  complementary DNA strands, 679
  D-deoxyribose (sugar component), 674
  defined, 673
  double helix, 678, 678*f*
  hydrogen bonding, 679, 679*f*
  intron/exon, 689, 689*f*
  mutations, 695–696
  Okazaki fragment, 683
  plasmids, 698, 698*f*
  polymerase chain reaction (PCR), 683–684
  recombinant, 696–699
  replication, 680–684
  RNA, contrasted, 684
  secondary structure, 678–680
  sequencing, 690
  structure, 676–680
  tetranucleic structures, 677*f*
  trinucleic structures, 676–677
  Watson-Crick structure, 678, 678*f*, 680
DNA checkup, 690
DNA double helix, 678, 678*f*
DNA ligase, 698
DNA palindrome, 697
DNA polymerase I, 653*t*
DNA replication, 680–684
DNA sequencing, 690
Docosahexaenoic acid (DHA), 586*t*, 765

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Dopa, 524
Dopamine, 524, 775, 775*t*
Double bonds, 109
Double helix, 678, 678*f*
Double-replacement reaction, 147, 147*f*
Doudna, Jennifer, 697
DRVs. *See* Daily Reference Values (DRVs)
Dry ice, 185
DSHEA. *See* Dietary Supplement Health and Education Act (DSHEA)
DVs. *See* Daily Values (DVs)
Dynamite, 498

E

E. coli, 661–662
EC classification. *See* Enzyme Commission (EC) classification of enzymes
ECMO. *See* Extracorporeal membrane oxygenation (ECMO)
Eddington, Arthur, 324
EDTA. *See* Ethylenediaminetetraacetic acid (EDTA)
Effective collision, 244
Effusion, 181
Eicosapentaenoic acid, 586*t*
Einstein, Albert, 321
Einstein's famous equation (E = mc^2), 321
Elastase, 660*t*
Elastin, 627
Electrical conductivity of solutions, 218–219
Electrolyte balance, 799–801
Electrolytes, 218*f*, 219
Electron capture, 308
Electron transfer, 102, 144
Electron transport chain, 746–747, 747*f*
Electronegativity, 118, 118*t*
Electronegativity difference (Δ*EN*), 120
Electronic configurations, 78–82, 84*f*, 97–99
Electronic-dot formulas, 98. *See also* Lewis structures
Electrons
  arrangements of electron pairs aro0und central atom, 114*f*
  characteristics, 50*t*
  defined, 50
  distinguishing, 83
  double and triple bonds, 109
  electron occupancy of shells, 76*t*
  electronic configurations, 78–82
  energy of, located in an orbital, 75
  filling order, 78, 78*f*
  first ionization energy, 89
  fourth shell of an atom, 75*f*
  Hund's rule, 78
  increasing nuclear charge, 89
  losing and gaining, 100–101
  moving rapidly around massive nucleus, 51, 51*f*
  noble gas configuration, 81
  octet rule, 97, 99
  p or *d* orbitals, 74
  Pauli exclusion principle, 78
  shells, subshells, and orbitals, relationship with, 75*t*
  unpaired, 78, 79–80
  valence, 90, 98
  VESPR theory, 114–118
Element, 11, 12*f*
Elemental symbol, 48, 48*t*
Elimination reaction, 415
Emergency medical technicians (EMTs), 96, 130
Emollients, 359
EMTs. *See* Emergency medical technicians (EMTs)
Emulsifying agent, 224
Enantiomer, 548, 548*f,* 555, 557
End-of-chapter exercises, answers to, B-1 to B-60
Endergonic process, 238
Endothermic changes of state, 182, 182*f*
Endothermic reaction, 150, 243, 243*f*
Endothermic solution process, 207, 207*f*
Endpoint of a titration, 285
Energy
  activation, 240
  ATP. *see* Adenosine triphosphate (ATP)
  chemical reactions, 150
  first ionization, 89, 89*f*
  flow of energy in biosphere, 716–717
  free, 721, 722*t*
  high-energy compound, 721
  internal, 240, 240*f*
  ionization, 89
  kinetic, 168, 168*f,* 169, 186
  law of conservation of energy, 139
  nuclear, 321–325
  potential, 169, 169*f,* 186
  second ionization, 89
  states of matter, 186–190
  unit of, 18
Energy crash, 740
Energy diagram, 242–243, 242*f*
Energy drinks, 225, 241
Energy-releasing hydrolysis reaction, 721, 721*f*
Enflurane, 430
English units of length, 14, 14*t*
Entropy, 238
Entropy increase, 238
Environmental careers. *See* Health and environmental careers
Environmental Connections boxes
  carbon dioxide emissions (greenhouse effect), 227
  carbon dioxide in the oceans, 263
  carbon footprint, 359
  chemistry as central science, 5
  ozone, 127
  plastic pollution in world's oceans, 489
Enzyme, 646–670
  allosteric, 661
  allosteric regulation, 661
  catalytic efficiency, 647
  catalyzed vs. uncatalyzed reactions, 647*f*
  coenzyme, 650, 651*t*
  cofactors, 650–651
  concentration, 653–654, 654*f*
  defined, 647
  EC classification, 648, 649*t*
  enzyme international unit (IU), 652–653
  factors affecting enzyme activity, 653–655
  genetic control, 661–662
  induced-fit theory, 652, 652*f*
  irreversible inhibition, 655–656, 662
  isoenzyme, 663–664
  lock-and-key theory, 652, 652*f*
  mechanism of enzyme activity, 651–652
  medical diagnosis, 663, 663*t*
  medical uses, 663–664
  nomenclature, 648–649
  pH, 654–655, 654*f*
  regulation, 648, 660–662
  restriction, 696–698
  reversible inhibition, 656–660, 662
  specificity, 647–648
  substrate concentration, 654, 654*f*
  temperature, 654, 654*f*
  turnover number, 652, 653*t*
  zymogens, 660, 660*t*
Enzyme activity, 652
Enzyme assays, 652, 663, 663*t*
Enzyme-catalyzed hydrolysis, 494
Enzyme Commission (EC) classification of enzymes, 648, 649*t*
Enzyme concentration, 653–654, 654*f*
Enzyme induction, 661
Enzyme inhibition, 655–660, 662
Enzyme inhibitor, 655–660, 662
Enzyme international unit (IU), 652–653
Enzyme specificity, 647–648
Enzyme-substrate (ES) complex, 651
Epidermin, 630
Epinephrine, 525, 755, 755*t,* 775*t*
Epsom salts, 277*t*
Equilibrium, 183. *See also* Reaction rates and equilibrium
Equilibrium concentrations, 246
Equilibrium constant, 247, 248–249, 250
Equilibrium expression, 247, 248
Equivalence point of a titration, 285, 287*f*
Erythrose, 550
D-erythrose, 554
L-erythrose, 554
Erythrulose, 556, 556*f*
ES complex. *See* Enzyme-substrate (ES) complex
Escherichia coli, 661–662
Essential amino acids, 711, 711*t,* 783*t*
Essential fatty acids, 585
Ester formation, 488, 491
Ester hydrolysis, 493–494
Ester linkage, 487
Esterification, 487, 588
Esters. *See also* Carboxylic acids and esters
  carboxylic, 487–492
  defined, 497
  ester linkage, 487
  esterification, 487
  formation, 488, 491
  functional group, 338*t*
  hydrolysis/hydrolysis reactions, 493–494
  inorganic acids, 497–499
  nomenclature, 492–493
  phosphate, 497–499
  saponification/saponification reactions, 495–496
  structural formula, 338*t*
Estradiol, 606
Estrogens, 606
Estrone, 606
Ethanal, 449*t*
Ethanamide, 528
Ethane, 338*t,* 341, 341*f,* 345*t,* 346, 347*t,* 358*t*
Ethanedioic acid, 480*t*
1,2-ethanediol, 411, 424, 425*t*
Ethanoic acid, 480*t,* 485, 528
Ethanol, 409, 415, 422–423, 425*t,* 742
Ethanolamine, 596, 775, 775*t*
Ethene, 374*f,* 377*f,* 378, 380*t*
Ethers
  alcohols, 417–418
  alkoxy group, 428
  boiling point, 482*t*
  functional group, 338*t*
  general anesthetics, 430
  heterocyclic ring, 429
  hydrogen bonding, 429
  naming, 428–429
  properties, 429–430
  structural formula, 338*t*
Ethoxy, 428, 429
2-ethoxybutane, 428
N-ethyl-*N*-methylbenzamide, 529
Ethyl alcohol, 336, 336*f,* 338*t,* 410, 422, 425*t*
Ethyl ether, 428, 430
Ethyl group, 346, 347*t*
Ethyl methyl ether, 428
2-ethyl-1-pentanol, 411
2-ethyl-1-pentene, 375
2-ethyl-*N*-methylaniline, 513
3-ethyl-*N*-methylaniline, 530
Ethylamine, 514*t*
Ethylbenzene, 394
2-ethylbutanal, 449
3-ethylcyclopentene, 375
Ethyldimethylammonium bromide, 517
Ethylene, 338*t,* 373, 374, 374*f,* 377*f,* 387
Ethylene glycol, 411, 411*f,* 424, 424*f,* 425*t*
Ethylenediaminetetraacetic acid (EDTA), 656
Ethylmethylamine, 512
3-ethyltoluene, 396
m-ethyltoluene, 396
Ethyne, 390, 390*f*
Eukaryotic cell, 600
Euphorbia resinifera, 463
Exercises, end-of-chapter, answers, B-1 to B-60
Evaporation, 183, 183*f*
Exact numbers, 27
Excedrin Aspirin Free, 522
Exergonic process, 238
Exon, 689, 689*f*
Exothermic changes of state, 182, 182*f*
Exothermic reaction, 150, 242, 243*f*
Exothermic solution process, 207, 207*f*
Expanded structural formula, 337, 338*t*
Expanding or branching chain reaction, 321
Extracellular fluid, 793
Extracorporeal membrane oxygenation (ECMO), 792
Eye shadow, 594*f*

F

Facial cleansers, 483*f*
Factor-unit calculations, 60–61
Factor-unit method, 28–30
Factors, 28
FAD. *See* Flavin adenine dinucleotide (FAD)
FADH$_2$, 727, 729, 769, 770
Fahrenheit scale, 16, 17*f*
Family, 71
Faraday, Michael, 392
Fat mobilization, 766–767
Fat-soluble vitamins, 712, 713*t*
Fats and oils, 588–594
  definitions, 589
  excessive fat in the diet, 589
  fatty acid composition of common food fats, 710*f*
  hydrogenation, 592–594
  hydrolysis, 590
  important dietary sources of energy, 763
  saponification, 591, 592
  triglycerides. *see* Triglycerides
Fatty acid degradation, 773
Fatty acid spiral, 768*f,* 769
Fatty acid synthesis, 773–774
Fatty acid synthetase system, 774
Fatty acids
  calculations, 770
  defined, 479, 584–587
  energy derived from, 770–771
  essential, 585
  fatty acid composition of common food fats, 710*f*
  micelles, 479, 480*f*
  molecular structure, 479*f*
  monounsaturated fatty acids (MUFAs), 586*t,* 606
  omega-3/omega-6, 586*t,* 587
  oxidation, 767–770
  polyunsaturated, 585, 586*t*
  saturated/unsaturated, 585, 586*f,* 586*t,* 589*f*
  space-filling models, 586*f*
  synthesis, 773–774
  trans fats, 594
Fatty fish, 765
Feedback inhibition, 661, 661*f*

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Fermentation, 423, 742*f*
Fermi, Enrico, 321, 322
Ferric chloride, 105*f*
Ferritin, 626
Ferrous chloride, 105*f*
Ferrous fumarate, 119
Ferrous gluconate, 119
Ferrous sulfate, 119
Fertilizer, 282*f*
Fiber, 571
Fibrin, 630
Fibrous proteins, 627, 627*f*
Field chemist, 164, 190
Fight-or-flight hormone, 525
Filling order, 78, 78*f*, 80, 80*f*
Film badge, 314, 314*f*
First ionization energy, 89, 89*f*
Fischer, Emil, 552
Fischer projections, 552–553, 557*f*
Fishy odor, 515*f*
Fission-powered generating plant, 324, 324*f*
Fission reactors, 324
Fission-type nuclear bombs, 323, 323*f*
5’ end, 676, 693*f*, 694*f*
Flavin adenine dinucleotide (FAD), 727–729
Flavin mononucleotide (FMN), 746
Fleming, Alexander, 656
Fluffo, 592
Fluid and electrolyte balance, 799–801
Fluid-mosaic model, 600, 601*f*
Fluoride, 152
Fluorine, 715*t*
Fluoro group, 347*t*
fMet. *See* *N*-formylmethionine (fMet)
FMN. *See* Flavin mononucleotide (FMN)
Foams, 487
Folacin, 651*t*
Folic acid, 657, 658, 658*f*, 659, 713*t*
Follicle-stimulating hormone (FSH), 625*t*
Food label, 707, 708*f*
Food spoilage, 245
“Fool’s gold,” 49*f*
Forces between particles, 96–137
  covalent bonding, 107–109
  electron transfer processes, 102
  electronegativity, 118, 118*t*
  electronic configurations, 97–99
  ionic bonding, 99–101
  ionic compounds. *see* Ionic compounds
  Lewis structures. *see* Lewis structures
  losing and gaining electrons, 100–101
  naming binary covalent compounds, 122–124
  naming binary ionic compounds, 104–105
  noble gas configurations, 97, 100
  octet rule, 97, 99
  other interparticle forces, 125–129
  polar/nonpolar covalent bonds, 118, 120, 120*f*
  polar/nonpolar molecules, 121, 121*t*, 123
  polarity of covalent molecules, 118–121
  polyatomic ions. *see* Polyatomic ions
  VESPR theory, 114–118
Formaldehyde, 448*f*, 449*t*, 464
Formalin, 464
Formamide, 528, 530
Formic acid, 283*t*, 291*t*, 480*t*, 481*t*, 483*f*, 528
Formica, 397*t*, 464
Formicine ants, 483*f*
Formulas and symbols, 47–49
N-formylmethionine (fMet), 693
Fortified cereal, 100*f*
Fortrel, 490
Four R’s: Reduce, Reuse, Recycle, and Refuse, 359
Fragrant odors (flavoring), 464, 464*f*, 465*t*, 487*f*
Franklin, Rosalind, 678
Free energy, 721, 722*t*
Free radicals, 311
Freeze drying, 185
Freezing point, 219–221
Fructose, 447, 557, 558*t*, 564
Fructose-6-phosphate, 562
Fruit juice, 225
Fruit punch, 225
Fruit ripening, 245
Fruits and vegetables, 150, 656*f*
FSH. *See* Follicle-stimulating hormone (FSH)
Fukushima nuclear disaster, 324
Fumarate, 657
Fumaric acid, 385
Functional groups, 336–339, 434, 458
Furan, 429
Furanose ring, 559
Fusion reactions, 324
Fusion reactors, 325

G

(g), 139
β-galactosidase, 661–662
Galactose, 558*t*, 564
β-D-galactose, 564
Gallium (Ga), 320, 321
Gallstones, 603, 603*f*
Gamma radiation, 306
Gamma rays, 305, 305*f*, 306, 306*t*, 308
Ganglioside G_{M2}, 600*t*
Garlic, 431, 431*f*
Gas laws, 171–174
Gases, 166*f*, 167*t*, 170–171, 170*f*
Gasohol, 423
Gasoline, 360
Gastrin, 625*t*
Gastroesophageal reflux disease (GERD), 284
Gaucher’s disease, 600*t*
Geiger-Müller tube, 315, 315*f*
Gels, 223, 487
Gene, 680
Gene editing, 697
General anesthetics, 430
Genetic code, 687, 690–692
Genetic engineering, 696–699
Genetic mutations, 695–696
Gentiobiose, 566
GERD. *See* Gastroesophageal reflux disease (GERD)
GI. *See* Glycemic index (GI)
Glass-cleaning products, 263*f*
Glauber’s salt, 277*t*
Global warming, 227
Globular proteins, 627
Glucagon, 625*t*, 754, 755*t*
Glucocorticoids, 604
Glucogenic amino acid, 780*f*, 781
Gluconeogenesis, 753, 754*f*, 775
Glucose
  alcoholic fermentation, 742
  aldohexose, 556
  ATP production, 749–750
  Benedict’s test, 455
  blood, 737–738, 738*f*
  blood sugar levels, 737–738, 740
  cane sugar, 447
  complete oxidation, 749–750
  gluconeogenesis, 753, 754*f*
  lactate fermentation, 742
  molecular formula, 625
  polyfunctional compound, 433
  relative sweetness, 558*t*
  sweetener, 564
Glucose-6-phosphate, 497, 562
α-D-glucose, 558, 559
β-D-glucose, 558, 559, 564
D-glucose, 554, 559
L-glucose, 554
β-glucosidase, 655*t*
Glucosuria, 738, 799*t*
Glues, 223
Glutamate, 617*t*, 776, 783*t*
Glutamate dehydrogenase, 776
Glutamic acid, 691*t*
Glutamine, 616, 617*t*, 691*t*, 783*t*, 784
Glycemic index (GI), 740
D-glyceraldehyde, 548*f*, 552*f*, 556
L-glyceraldehyde, 548*f*, 552*f*
Glycerin, 424, 425*t*
Glycerol, 357, 424, 425*t*, 588, 591
Glycerol metabolism, 767
Glyceryl tristearate, 588
Glycine, 617*t*, 691*t*, 783*t*
Glycogen, 570, 570*f*
Glycogen breakdown, 751–752
Glycogen metabolism, 751–752
Glycogen synthesis, 751
Glycogenesis, 751
Glycogenolysis, 751–752
Glycolic acid, 483*f*
Glycolipids, 598, 599, 600*t*
Glycolysis, 738–740, 767
Glycolysis pathway, 738, 739*f*
Glycoproteins, 628, 628*t*
Glycoside, 553, 562
Glycosidic linkage, 562, 563
Glycylalanine, 622, 623
Gold, 238*f*
Golf club, 339*f*
Good/bad ozone, 127
Good cholesterol, 765
Gore-Tex, 387*f*
Gossamer Albatross, 490*f*
Graham, Thomas, 181
Graham’s law, 181–182
Grain alcohol, 336, 336*f*
Gram (g), 15
Graphite, 319
Graphite fibers, 339*f*
“Gravity hill” (Salt Lake City), 237
Gray (Gy), 313, 314*t*
Great Pacific Garbage Patch, 489
Greek numerical prefixes, 122*t*
Greenhouse effect, 227
Greenhouse gases, 227
Group, 71, 76*f*, 76*t*, 77, 82
Group IA(1), 82, 84*f*, 88, 89, 90*f*
Group VA(15), 84*f*, 87*f*
Group VIA(16), 128
Group VIIA(17), 84*f*, 87*f*
Growth hormone, 626
Guanine, 674, 674*f*
Gum, 557*f*
Gypsum, 277*t*

H

H2 blockers, 284
Hahn, Otto, 321
Half-life, 309–311, 774–775
Hallucinations, 526
Haloalkane, 380
Halogenation, 380
Halogenation reactions, 381–382
Halons, 127
Ham, 650
Hand cream, 594*f*
Hand sanitizers, 427
Hard soaps, 591
Harvard Health Publications, 34
Hawthorne structure, 558, 560
HCFCs. *See* Hydrochlorofluorocarbons (HCFCs)
HCl. *See* Hydrochloric acid (HCl)
HDL. *See* High-density lipoprotein (HDL)
Health. *See* Human health
Health and environmental careers
  allergy/immunology nurse, 510, 534–535
  anesthesiologist assistant, 372, 398
  apiarist, 330, 361–362
  avian field technician, 672, 699
  beekeeper, 330, 361–362
  clinical laboratory technician, 138, 157
  clinical laboratory technologist, 157
  dental assistant, 546, 572
  EMTs, 96, 130
  field chemist, 164, 190
  nuclear medicine technologist, 304, 325
  nurse practitioner (NP), 446, 465–466
  nutritionist/nutrition therapist, 706, 730
  paramedic, 96, 130
  pediatric nurse, 762, 784–785
  perfusionist, 792, 806
  personal care product developer, 198, 227–228
  pharmacy technician, 478, 499
  physical therapy assistant (PTA), 582, 607
  physician’s assistant (PA), 236, 252
  radiologic technician, 70, 91
  radiologist, 70, 91
  registered nurse (RN), 646, 665
  rehabilitation counselor/technician, 408, 434–435
  respiratory therapist (RT), 260, 292
  sonographer, 736, 755
  sterile processing technician, 2, 35
  wildlife technician, 46, 64
Health Connections boxes. *See also* Human health
  aspirin, 495
  aspirin substitutes, 522
  blood pressure reading, 174
  bone health, 54
  chocolate, 528
  diagnostic radiation, 308*f*, 314
  DNA checkup, 690
  effects of temperature on body functions, 19
  energy crash, 740
  energy drinks, 241
  fiber, 571
  fiber supplements, 728
  foods for the brain, 765
  fruits and vegetables, 150
  gene editing, 697
  general anesthetics, 430
  hand sanitizers, 427
  heart-healthful diet, 714
  heartburn, 284
  herbs, 53
  high-protein diet, 621
  interaction between alcohol and antidepressants, 424
  iron preparations, 119
  juices and sports drinks, 225
  lactate accumulation, 745
  lactose intolerance, 658
  Mediterranean diet, 103
  milk, 632
  moisturizers, 357
  nitroglycerin, 498
  olive oil, 606
  organic food, 340
  phenylalanine and diet foods, 782
  phenylketonuria (PKU), 781
  processed meat, 650
  pulse oximetry, 800
  radon in the home, 318
  salt, 74
  stay hydrated, 210
  sugar-free foods and diabetes, 561
  tanning lotions and creams (chemical tans), 451
  tanning salons, 395
  teeth whitening, 152

  - therapeutic uses of oxygen gas, 187
  - 3-D printers, 378
  - trustworthiness of websites, 34
  - using smartphone to help you stay healthy, 246
  - vanilloids, 463
  - zinc for colds?, 85
- Healthful diets, 103
- Heartburn, 284
- Heat calculation, 187, 192
- Heat of fusion, 188
- Heat of reaction, 243*f*
- Heat of vaporization, 188
- Heavy-metal poisoning, 656
- Heet, 463
- Hematuria, 799*t*
- Heme group, 635*f*, 795, 795*f*
- Heme structures, 775
- Hemiacetals, 456, 457, 459, 460
- Hemiketals, 457, 459, 460
- Hemlock herb, 526
- Hemodialysis, 799*f*
- Hemoglobin
  - deoxyhemoglobin, 794
  - globular protein, 627
  - nitrogen-containing biomolecule, 775
  - protein chain, 795*f*
  - quaternary protein structure, 634, 635*f*
  - size, 625
  - transport function, 626
- Hemoglobinuria, 799*t*
- Hemoproteins, 628*t*
- Henderson-Hasselbalch equation, 290, 291
- hepta-, 122*t*
- Heptane, 345*t*, 358*t*
- 1-heptanol, 414
- Herbs, 53
- Heroin, 527
- Herring, 765
- Hertz (Hz), A-1
- Heteroatomic molecules, 8
- Heterocyclic ring, 429
- Heterogeneous catalyst, 245
- Heterogeneous matter, 10
- Heterogeneous nuclear RNA (hnRNA), 689, 689*f*
- hexa-, 122*t*
- Hexagon, 354
- Hexane, 345*t*, 346, 358*t*
- *n*-hexane, 346
- Hexanoic acid, 480*t*
- Hexatriene, 376
- 1-hexene, 380*t*
- Hexose, 556*t*
- 4-hexylresorcinol, 426
- High-density lipoprotein (HDL), 766*f*
- High-density polyethylene, 387*f*
- High-energy compound, 721
- High-protein diet, 621
- High-sugar drinks, 225
- Hiroshima, Japan (nuclear bomb), 323
- Histamine, 775*t*
- Histidine, 617*t*, 691*t*, 711*t*, 775*t*, 783*t*
- hnRNA. *See* Heterogeneous nuclear RNA (hnRNA)
- Homoatomic molecules, 8
- Homogeneous catalyst, 245
- Homogeneous matter, 10
- Homogeneous mixtures, 10
- Homologous series, 357
- Homovanillyl group, 463
- Honey, 567*f*
- Honeybees, 361
- Hormone, 604
- Hot air balloons, 345*f*
- Hot dogs, 650
- Hot peppers, 463
- Hot spot, 315
- Hotels analogy, 81
- Household cleaning agents, 263*f*
- Human body
  - body temperature, 19
  - bones, 54
  - carbon, 58*f*
  - chemical elements, 47*f*
  - effects of temperature on body functions, 19
  - water, 114*f*
- Human Genome Project, 690
- Human growth hormone (HGH), 625*t*
- Human health. *See also* Health Connections boxes
  - abnormal urine constituents, 799*t*
  - angina pectoris, 498
  - blood pressure reading, 174
  - cancer-producing compounds, 396–397
  - common cold, 85
  - cryogenic surgery, 173*f*
  - decompression sickness, 173, 203
  - dialysis, 227
  - diseases originating from accumulation of lipids, 600*t*
  - gallstones, 603, 603*f*
  - GERD, 284
  - hyperbaric therapy, 173
  - lactose intolerance, 658
  - laparoscopic surgery, 176
  - medical diagnosis, 663, 663*t*
  - minimally invasive surgery, 115
  - osteoporosis, 54
  - phenylketonuria (PKU), 781, 782
  - polymerase chain reaction (PCR), 683–684
- Humectants, 357
- Hummingbirds, 567*f*
- Hund, Friedrich, 79*f*
- Hund's rule, 78
- Hybrid orbital, 334, 335*f*
- Hydrated ion, 205
- Hydration, 210, 385
- Hydration reactions, 386
- Hydrobromic acid, 281*t*
- Hydrocarbon, 339
- Hydrochloric acid (HCl), 262*f*, 264, 271*t*, 281*t*, 290*f*, 516
- Hydrochlorofluorocarbons (HCFCs), 127
- Hydrogen
  - aldehydes and ketones, 455–456
  - ionizable hydrogens, 282, 283
  - isotopes, 51
  - numerical data related to gaseous state, 171*t*
  - specific heat, 188*t*
- Hydrogen-2, 325
- Hydrogen bond, 129*f*, 452
- Hydrogen bonding, 126, 127*f*, 128
  - alcohols, 414, 414*f*
  - amides, 530–531
  - amines, 514, 515
  - DNA, 679, 679*f*
  - ethers, 429
  - proteins, 629, 632–633
- Hydrogen borate ion, 291*t*
- Hydrogen chloride, 264
- Hydrogen citrate ion, 291*t*
- Hydrogen peroxide, 152
- Hydrogen phosphate ion, 291*t*
- Hydrogen sulfide, 264, 264*f*
- Hydrogenation
  - aldehydes and ketones, 456
  - alkenes, 382
  - fats and oils, 592–594
- Hydrogenation reactions, 382–383, 456
- Hydrolases, 649*t*
- Hydrolysis
  - adenosine triphosphate (ATP), 721–723
  - aldehydes and ketones, 461, 462
  - amides, 532, 533
  - digestion, 718, 719*f*
  - disaccharides, 564
  - energy-releasing hydrolysis reaction, 721, 721*f*
  - esters, 493–494
  - fats and oils, 590
  - free energy changes for hydrolysis of phosphate compounds, 722*t*
  - proteins, 636
  - salts, 288–289
  - urea, 648*f*, 649
- Hydrolysis reactions, 532, 533
  - aldehydes and ketones, 462
  - amides, 533
  - defined, 288
  - esters, 494
  - fats and oils, 590
  - salts, 288–289
- Hydrophobic, 359
- Hydrophobic interactions, 633, 633*f*
- Hydrosulfuric acid, 264
- 2-hydroxy-1,2,3-propane-tricarboxylic acid, 480*t*
- β-hydroxybutyrate, 771, 772*f*
- Hydroxyl group, 409
- 2-hydroxypropanoic acid, 480*t*
- Hyperbaric oxygenation, 187
- Hyperbaric therapy, 173, 187
- Hyperglycemia, 738
- Hyperthyroidism, 316
- Hyperventilation, 802
- Hypo, 277*t*
- Hypoglycemia, 738
- Hypothermia, 19
- Hypoventilation, 802

I

- Ibuprin, 522
- Ibuprofen, 522
- Ice cream, 487
- Icebergs, 128*f*
- Ideal gas law, 178–180
- Ideal gases, 180
- Illness/disease. *See* Human health
- Immiscible, 201
- Immunology nurse, 510, 534–535
- In equilibrium, 183. *See also* Reaction rates and equilibrium
- Induced dipoles, 128, 129
- Induced-fit theory, 652, 652*f*
- Induced nuclear reactions, 318–321
- Indy-style racing cars, 422, 422*f*
- Inhibitor, 245
- Initiation complex, 693
- Inner-transition element, 84, 84*f*
- Inorganic chemistry, 332
- Inorganic compound, 332–333, 333*t*
- Insoluble substance, 201
- Insulin, 625*t*, 629, 629*f*, 754, 755*t*
- *Interceptor,* 489
- Internal energy, 240, 240*f*
- International Atomic Energy Agency (IAEA), 325
- International Ice Patrol, 128*f*
- International System of Units (SI units), 13, A-1
- International Union of Pure and Applied Chemistry (IUPAC) system. *See* IUPAC name
- Interparticle forces. *See* Forces between particles
- Interstitial fluid, 793, 793*f*, 798*f*
- Intracellular fluid, 793, 793*f*
- Intron, 689, 689*f*
- Inverse square law of radiation, 312
- Invert sugar, 558*t*, 567
- Iodine, 87*f*, 715*t*, 716*f*
- Iodine-123, 307, 315, 316
- Iodine-131, 316
- Iodo group, 347*t*
- Ion
  - ammonium, 124
  - anion, 276
  - carboxylate, 483
  - cation, 276
  - defined, 89
  - hydrated, 205
  - magnesium, 101*t*
  - noble gas configurations, 100
  - polyatomic. *see* Polyatomic ions
  - simple, 99
  - spectator, 149
- Ion product of water, 266
- Ionic bond, 99, 120, 120*f*, 129*f*
- Ionic bonding, 99–101
- Ionic compounds, 101–103
  - formula weights, 106
  - formulas, 105
  - lattice site/crystal lattice, 106, 106*f*
  - molecular compounds, compared, 106–107
  - naming, 104–105
- Ionic equations, 148–149
- Ionic equilibrium equations, 273
- Ionizable hydrogens, 282, 283
- Ionization energy, 89
- Iron, 715*t*, 716*f*
- Iron deficiency anemia, 119
- Iron preparations, 119
- Iron pyrite, 49*f*
- Irreversible inhibition, 655–656, 662
- Isobutane, 342*f*, 345, 346, 347*t*
- Isobutyl group, 347*t*
- Isocitrate dehydrogenase, 745
- Isoelectric point, 619
- Isoelectronic, 101
- Isoenzyme, 663–664
- Isohexane, 346
- Isoleucine, 617*t*, 661, 661*f*, 691*t*, 711*t*, 783*t*
- Isomerases, 649*t*
- Isomerism, 335
- Isopentane, 346
- Isopropyl alcohol, 410, 413, 414*f*, 423, 423*f*, 425*t*
- Isopropyl group, 347, 347*t*
- Isopropyl phenyl ether, 428
- Isopropyl rubbing alcohol, 211*f*
- 2-isopropyl-5-methylphenol, 396
- 5-isopropyl-2,3-dimethyloctane, 350
- Isotope, 51, 55–56
- Isotope half-life, 309–311
- IU. *See* Enzyme international unit (IU)
- IUPAC name, 71. *See also* Names
  - alcohols, 410–412
  - aldehydes, 448–449
  - alkanes, 345–352
  - alkenes, 374–376
  - alkyl groups, 346
  - alkynes, 391
  - amides, 528–530
  - amine salts, 517
  - amines, 512–513
  - anilines, 513
  - aromatic compounds, 393–396
  - benzene derivatives, 393–396, 399
  - carboxylic acid salts, 485–486
  - carboxylic acids, 479–481
  - cycloalkanes, 352, 353–354
  - esters, 492–493
  - ethers, 428–429
  - ketones, 450
  - larger alkanes, 345, 345*t*
  - organic compounds, 346
  - phenols, 412

J

- Jaundice, 799*t*
- Jelly, 487
- Jelly beans, 59*f*
- Jobs. *See* Health and environmental careers
- Joliot-Curie, Frederic, 318, 319*f*
- Joliot-Curie, Marie, 313*f*, 318, 319*f*
- Joule (J), 18, A-1
- Juices, 225

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

K

- K_a, 282, 290, 291, 291*t*
- Kekulé, Friedrich August, 392
- Kekulé structures, 392, 393
- Kelvin temperature scale, 16, 17*f*
- Keratin, 626, 627
- α-keratin, 627*f*, 630
- β-keratin, 627*f*
- Ketal, 457, 461
- Ketoacidosis, 773
- Ketogenic amino acid, 780*f*, 781
- Ketone bodies, 771–773
- Ketonemia, 772
- Ketones, 447. *See also* Aldehydes and ketones
- Ketonuria, 772, 799*t*
- Ketopentose, 556
- Ketose, 556
- Ketosis, 772
- Kevlar, 522, 522*f*
- Kidney dialysis, 227
- kilo-, 14*t*
- Kilogram (kg), 15
- Kinetic energy, 168, 168*f*, 169, 186
- Kinetic molecular theory of matter, 168–169, 173
- Kossel, Walther, 97, 99, 99*f*
- Krebs, Hans A., 743, 743*f*
- Krebs cycle, 743
- Kwolek, Stephanie, 522*f*

L

- *(l)*, 139
- L and D compounds, 552–556
- Lactaid, 658
- Lactate accumulation, 741–742, 745
- Lactate dehydrogenase (LDH), 651, 653*t*, 663, 663*t*, 664
- Lactate fermentation, 742
- Lactic acid, 291*t*, 357, 480*t*, 484
- D-lactic acid, 553, 555
- L-lactic acid, 553, 555
- Lactose, 558*t*, 565–566, 568*t*
- Lactose intolerance, 658
- Landfill, 190
- Laparoscopic surgery, 176
- Lattice site, 106
- Laughing gas, 430
- Lauric acid, 481*t*
- Law of conservation of energy, 139
- LDH. *See* Lactate dehydrogenase (LDH)
- LDL. *See* Low-density lipoprotein (LDL)
- Le Châtelier's principle, 250–251, 252, 483, 659, 795, 796, 804
- Lead poisoning, 656
- Lead salts, 637
- Leading zeros, 24, 24*f*
- Lean meats, 714
- Learning Checks, solutions, C-1 to C-22
- Lecithins, 595, 596*f*
- LED bulbs, 359
- LES muscle. *See* Lower esophageal sphincter (LES) muscle
- Leucine, 617*t*, 691*t*, 711*t*, 783*t*
- Levorotatory, 555
- Levulose, 564
- Lewis, G. N., 97, 98, 98*f*, 99, 107
- Lewis structures
  - atomic, 109*t*
  - defined, 98
  - drawing, 98, 109, 110–111
  - molecular, 109*t*
  - polyatomic ions, 112–113
  - reactions, and, 108
  - shared electron pairs/nonshared pairs, 107
  - valence-shell electrons, 98
- Ligases, 649*t*
- Limiting reactant, 153–155
- Limiting-reactant principle, 154
- Linear particle accelerator, 320, 320*f*
- Linoleic acid, 585, 586*f*, 586*t*, 587, 774
- Linolenic acid, 585, 586*t*, 587, 774
- Lip balm, 594*f*
- Lipase, 663*t*
- Lipid and amino acid metabolism, 762–791
  - amino acid biosynthesis, 783–784
  - amino acid catabolism (carbon skeleton), 780–782
  - amino acid catabolism (nitrogen atoms), 776–779
  - amino acid metabolism, 774–775
  - blood lipids, 763–766
  - chylomicron, 763, 764, 766*f*
  - deamination, 777–778
  - digestion and absorption of triglycerides, 764, 786
  - energy from fatty acids, 770–771
  - fat mobilization, 766–767
  - fatty acid spiral, 768*f*, 769
  - fatty acid synthesis, 773–774
  - four classes of lipoproteins, 765*f*, 766*f*
  - glycerol metabolism, 767
  - ketone bodies, 771–773
  - oxidation of fatty acids, 767–770
  - transamination, 776–777
  - urea cycle, 778–780
- Lipid bilayer, 600, 601*f*
- Lipids, 582–613, 710–711
  - adrenocorticoid hormones, 604–605
  - bile salts, 603
  - biological membranes, 600–602
  - blood lipids, 763–766
  - characteristics, 583
  - cholesterol, 602
  - classifying, 583–584
  - defined, 583
  - energy storage, 771
  - fats and oils. *see* Fats and oils
  - fatty acids. *see* Fatty acids
  - metabolism. *see* Lipid and amino acid metabolism
  - olive oil, 606
  - overview, 584*f*
  - phosphoglycerides, 594–597
  - prostaglandins, 606–607
  - sex hormones, 605–606
  - simple/complex, 583
  - sphingolipids, 597–600
  - steroid hormones, 604–606
  - steroids, 602–604
  - waxes, 594, 594*f*
- Lipoic acid, 651*t*
- Lipoproteins, 628, 628*t*
- Liquid helium, 97*f*
- Liquid-in-glass thermometer, 166
- Liquids, 166*f*, 167*t*, 170, 170*f*
- Lister, Joseph, 426
- Liter, 15, 15*f*
- Liver, 738, 774, 783
- Lock-and-key theory, 652, 652*f*
- Long-chain alcohols, 414
- Longest chains, 347–349
- Low-calorie drinks, 782
- Low-density lipoprotein (LDL), 764, 765*f*, 766*f*
- Low-molecular-weight amines, 515
- Lower esophageal sphincter (LES) muscle, 284
- Lowry, Thomas, 262
- Lucite, 387, 389*t*
- Lyases, 649*t*
- Lycopodium powder, 245*f*
- Lysine, 617*t*, 691*t*, 711*t*, 783*t*
- Lysol, 426
- Lysozyme, 663*t*

M

- M. *See* Molarity (M)
- Mackerel, 765
- Macronutrients, 707
- Magnesium
  - atomic weight, 57, 57*f*
  - fireworks, 5
  - member of group IIA(2), 76*f*
  - minerals in 60-kg person, 716*f*
  - overview, 715*t*
- Magnesium atom, 101*t*
- Magnesium ion, 101*t*
- Magnesium oxide, 146*f*
- Magnetic resonance imaging (MRI), 314
- Major minerals, 714, 715*t*
- Malic acid, 152, 385, 479
- Malonate, 657
- Malt sugar, 564. *See also* Maltose
- Maltose, 558*t*, 564–565, 568*t*
- Manganese, 715*t*, 716*f*
- Marathon runners, 766
- Marble statues, 272*f*
- Margarine, 382, 382*f*, 592*f*, 595
- Marijuana, 434
- Markovnikov, Vladimir, 383
- Markovnikov's rule, 383–386
- Mass
  - actual, 57
  - atom, 50
  - average, 56
  - defined, 4
  - total, 56
- Mass number, 51, 56
- Mass percentage calculations, 62–63
- Mass ratios and atomic weights, 58
- Mass spectrometer, 52
- Match, 246
- Matrix, 723
- Matter
  - classifying, 9–11, 12*f*
  - defined, 3
  - homogeneous/heterogeneous, 10
  - kinetic molecular theory, 168–169
  - model of, 7
  - observed properties, 166–168
  - physical properties, 5*f*
  - shape, 166
  - states of. *see* States of matter
- Mayo Clinic, 34
- Mayonnaise-like salad dressing, 224, 226
- Measurements, calculations, and numbers
  - basic/derived unit of measurement, 14
  - certainty/uncertainty, 25
  - converting non-scientific notation into scientific notation, 21
  - converting scientific notation into non-scientific notation, 20–21
  - exact numbers, 27
  - factor-unit method, 28–30
  - glassware for measuring volumes of liquids, 33*f*
  - measurement units, 13
  - metric system. *see* Metric system
  - percentages, 30–31
  - quantitative measurements, 13
  - rounding, 25
  - rulers, 23*f*
  - scientific calculator. *see* Calculator
  - scientific notation, 19, 22
  - SI units, 13, A-1
  - significant figures. *see* Significant figures
  - standard position, 19–20
  - temperature scales. *see* Temperature scales
  - units for measuring radiation, 313–314, 314*t*
- Meat, 650, 714
- Medical cannabis testing, 190
- Medical laboratory scientist, 138, 157
- Medical procedures. *See* Human health
- Mediprin, 522
- Mediterranean diet, 103, 765
- mega-, 14*t*
- Meitner, Lise, 321, 321*f*
- Melanin, 395, 775*t*
- Melting, 185
- Melting point, 125, 129, 185
- Membrane lipids, 600–602
- Mendeleev, Dimitri, 71, 71*f*
- Menten, Maud, 653*f*
- Menthacin, 463
- Menthol, 409, 416, 425*f*, 425*t*
- Menthone, 465*t*
- Mercaptans, 430
- Mercurochrome, 637
- Mercury, 637
- Mercury barometer, 171, 172*f*
- Mercury poisoning, 656
- Merthiolate, 637
- Messenger RNA (mRNA), 684–685, 685*t*. *See also* RNA
- Metabolic acidosis, 805, 805*t*
- Metabolic alkalosis, 805, 805*t*
- Metabolic pathway, 718
- Metabolism
  - amino acid, 774–775
  - carbohydrate. *see* Carbohydrate metabolism
  - defined, 718
  - glycerol, 767
  - glycogen, 751–752
- Metallic bond, 126, 129*f*
- Metalloids, 86, 86*f*
- Metalloproteins, 628, 628*t*
- Metals
  - activity series, 274, 274*t*
  - heavy-metal poisoning, 656
  - periodic table, 86, 86*f*
  - protein denaturation, 656
  - reducing hydrogen ions to hydrogen gas, 274*f*
- Metathesis reaction, 147, 147*f*
- Methanal, 449*t*
- Methanamide, 528
- Methandrostenolone (Dianabol), 605
- Methane, 345*t*, 346
  - alkyl group, 347*t*
  - molecular formula, 339
  - natural gas, 340, 431
  - physical properties, 358*t*
  - structural representation, 340*f*
- Methanoic acid, 480*t*, 483*f*, 528
- Methanol, 422, 425*t*
- Methedrine, 526
- Methicillin, 657*t*
- Methionine, 617*t*, 691*t*, 711*t*, 783*t*
- *N*-methylformamide, 529
- Methoxy group, 428, 429
- Methoxybenzene, 429
- *p*-methoxybenzoic acid, 428
- Methoxymethane, 428
- methyl-1(*trans*-2-butenyl)disulfide, 431
- 2-methyl-1,4-butanediol, 411
- 2-methyl-2-propanol, 413
- 2-methyl-*N*-propyaniline, 513
- 3-methyl-1-butanethiol, 431
- 3-methyl-1-butene, 375
- 3-methyl-1-butyne, 391
- 3-methyl-2-pentanone, 450
- *N*-methyl-2-butanamine, 512
- *N*-methyl-2-propanamine, 513
- Methyl acetate, 338*t*
- Methyl alcohol, 410, 422, 425*t*
- Methyl anthranilate, 487*f*
- Methyl bromide, 127
- Methyl chloroform, 127
- Methyl ether, 415, 428
- Methyl ethyl ketone (MEK), 449*t*
- Methyl group, 346, 347*t*
- Methyl phenyl ether, 428
- Methyl propyl disulfide, 432
- Methyl salicylate, 487*f*
- Methylamine, 338*t*, 512, 514*t*
- *N*-methylamphetamine, 526
- *N*-methylaniline, 513
- 3-methylbenzoic acid, 481
- *N*-methylbutanamide, 529
- 2-methylbutane, 350
- *N*-methylbutyramide, 529
- 2-methylcyclohexanone, 450
- 3-methylcyclohexanol, 411

- Methylcyclopentane, 353
- Methylene diphosphonate (technetium-99m-MDP), 325
- *N*-methylmethanamide, 529
- Metric system
  - advantages, 13
  - basic unit of mass, 15
  - commonly used metric units, 18*t*
  - expressing measurements in metric units, 16
  - expressing volume in metric units, 15
  - prefixes, 14*t*
  - SI units, 13
  - unit of energy, 18
  - units of length, 14, 14*t*
- Meyer, Julius Lothar, 71
- Micelles, 479, 480*f*
- Michaelis-Menton equation, 653*f*
- micro-, 14*t*
- Micronutrients, 707
- Microplastics, 489
- Migrating geese, 763*f*
- Milk, 225, 632
- Milk souring, 245
- Milk sugar, 565. *See also* Lactose
- milli-, 14*t*
- Milligram (mg), 15
- Mineral oil, 359
- Mineralocorticoids, 604
- Minerals, 714–716
- Mirror, 456, 456*f*
- mitochondrion, 723, 724*f*
- Mixture, 9, 10, 10*f*
- Model building, 7
- Moderately weak acids and bases, 281
- Moderators, 319
- Modified Bohr model, 91
- Modulator, 661
- Moisturizers, 357
- Molarity (M), 208–210, 270
- Mole (mol), 59
- Mole calculations, 64
- Mole concept
  - carbon dioxide, 60
  - chemical formulas, 61–63
  - chemical reaction formulas, 150–153
  - formula weights, 106
  - limiting-reactant principle, 153–155
  - number of moles, number of grams, number of atoms, 57–61
  - percentage yield calculations, 155–156
- Molecular collisions, 240–242, 242*f*, 244
- Molecular compounds, 106–107
- Molecular equation, 148
- Molecular formula, 49*t*, 61, 62, 106
- Molecular Lewis structure, 109*t*
- Molecular orbital, 108
- Molecular orientations during collisions, 241–242, 242*f*
- Molecular representations, 12*f*
- Molecular weight, 55, 106
- Molecular weight determination, 179, 192
- Molecules
  - defined, 7
  - molecular formula, 49*t*
  - molecular representation, 49*t*
  - molecular weight, 55
  - polar attractions, 184
  - polarity, 121, 121*t*
  - relative mass, 52–54
  - shape, 114–118
  - subdivision of, into smaller particles, 9
  - symbolic representations, 8*f*
  - types, 8
  - VESPR theory, 114–118
- Molybdenum, 715*t*
- Monester, 497
- mono-, 122*t*
- Monoamine oxidase inhibitors (MAOIs), 424
- Monomer, 387
- Monoprotic acid, 282, 283*t*
- Monosaccharides, 548*f*
  - aldo-/keto-, 556–557
  - chemical properties, 557–561
  - classifying, 556–557, 556*t*
  - defined, 548
  - deoxyribose, 563
  - fructose, 564
  - furanose ring, 559
  - galactose, 564
  - glucose, 564
  - glycosides, 553, 562
  - Hawthorne structure, 558, 560
  - oxidation, 560–561
  - phosphate esters, 562
  - physical properties, 557
  - polysaccharides, compared, 568*t*
  - pyranose ring, 558, 559
  - reducing sugars, 560
  - ribose, 563
  - sugars, 557, 558*t*
- Monounsaturated fatty acids (MUFAs), 586*t*, 606
- Morphine, 518, 527
- Morphine sulfate, 518
- Moth crystals, 185
- Motrin, 522
- Motrin IB, 522
- Mouthwash, 426
- MRI. *See* Magnetic resonance imaging (MRI)
- mRNA. *See* Messenger RNA (mRNA)
- MUFAs. *See* Monounsaturated fatty acids (MUFAs)
- Mullis, Kary, 683
- Muriatic acid, 262*f*
- Muscle meats, 714
- Mutagen, 696
- Mutation, 695–696
- Mylar, 490, 490*f*
- Myoglobin, 775
- Myosin, 630
- MyPlate, 707, 708*f*
- Myristic acid, 481*t*, 586*t*

N

- N-terminal residue, 623
- NAD^+. *See* Nicotinamide adenine dinucleotide (NAD^+)
- NADH, 725, 726, 769, 770
- Nagasaki bomb, 323
- Names
  - acids, 263–265
  - binary covalent compounds, 122
  - binary ionic compounds, 104–105
  - compounds containing ions, 124
  - enzymes, 648–649
  - Greek numerical prefixes, 122*t*
  - IUPAC name. *See* IUPAC name
  - phosphorus-containing acids, 265
  - stem names, 104, 104*t*
  - trivial or common names, 345
- nano-, 14*t*
- Naphthalene, 185, 396
- Naproxen, 522
- National Asthma Educator Certification Board, 534
- National Cancer Institute, 34
- National Center for Complementary and Alternative Medicine, 53
- National Institutes of Health, 53
- Native state, 636
- Natural gas, 340, 360, 431
- Natural method of teeth whitening, 152
- Naturally caffeinated drinks (tea/coffee), 241
- NCLEX-RN exam, 665
- ncRNA. *See* Non-coding RNA (ncRNA)
- Neon, 52*f*
- Neon atom, 101*t*
- Neotame, 561
- Neptunium, 320
- Nerve cell, 523*f*
- Net ionic equation, 149
- Network solids, 125
- Neuron, 522, 523*f*
- Neurotransmitters, 522–525
- Neutral, 265
- Neutralization reaction, 275
- Neutron, 50, 50*t*, 305, 306*t*, 319
- Neutron moderator, 319
- New England Journal of Medicine, 34
- Newton (N), A-1
- Newton, Isaac, A-1
- Niacin, 651*t*, 713*t*
- Niacinamide, 651*f*
- Nickel, 715*t*
- Nickel-60, 51
- Nicotinamide, 651*f*
- Nicotinamide adenine dinucleotide (NAD^+), 650–651, 651*t*, 725–726
- Nicotine, 526, 527
- Niemann-Pick disease, 600*t*
- Nirenberg, Marshall, 691
- Nitric acid, 262, 271*t*, 281*t*, 283*t*, 517
- Nitro group, 347*t*
- Nitrobenzene, 394
- Nitrogen, 87, 171*t*
- Nitrogen-13, 318
- Nitroglycerin, 498
- Nitrous acid, 281*t*
- Nitrous oxide, 430
- No-Doz, 527
- Nobel, Alfred, 498
- Noble gas configuration, 81, 97, 100
- Noble gases, 81, 84*f*
- Nomenclature. *See* Names
- Non-coding RNA (ncRNA), 687
- nona-, 122*t*
- Nonalkyl groups, 347*t*
- Nonane, 345*t*, 358*t*
- Noncompetitive inhibitor, 659, 659*f*
- Nonelectrolytes, 218*f*, 219
- Nonessential amino acids, 783, 783*t*
- Nonmetals, 86, 86*f*
- Nonpolar covalent bond, 118, 120, 120*f*
- Nonpolar molecule, 121, 121*t*, 123
- Nonpolar oils and greases, 226
- Nonredox combination reaction, 146
- Nonredox reactions, 141, 141*f*
- Nonsaponifiable lipids, 583
- Nonspontaneous process, 237*f*
- Norepinephrine, 524, 775*t*
- Normal alkane, 342
- Normal boiling point, 184
- NP. *See* Nurse practitioner (NP)
- Nuclear bombs, 323, 323*f*
- Nuclear chain reactions, 321–322, 322*f*
- Nuclear energy, 321–325
- Nuclear fission, 321, 325
- Nuclear fusion, 324, 325
- Nuclear magnetic resonance, 314
- Nuclear power plants, 324, 324*f*
- Nuclear processes. *See* Radioactivity and nuclear processes
- Nucleic acid backbone, 676, 676*f*, 677*f*
- Nucleic acids and protein synthesis, 672–705
  - bases of nucleic acids, 674, 674*f*, 675
  - components of nucleic acids, 673, 673*f*
  - DNA. *See* DNA
  - flow of genetic information, 687, 687*f*
  - general structure of nucleotide, 675
  - genetic code, 690–692
  - genetic engineering, 696–699
  - mutations, 695–696
  - nucleic acid, defined, 673
  - nucleic acid backbone, 676, 676*f*, 677*f*
  - Okazaki fragment, 682*f*, 683, 683*f*
  - polypeptide chain, 693–695
  - RNA. *See* RNA
  - sugars, 674–676
  - transcription, 688–689
  - translation, 693–695
  - translocation, 694, 694*f*
- Nucleoproteins, 628*t*
- Nucleotide, 673, 675
- Nucleus, 50
- Numbers. *See* Measurements, calculations, and numbers
- Nurse practitioner (NP), 446, 465–466
- Nursing careers
  - pediatric nurse, 762, 784–785
  - registered nurse, 646, 665
- Nutrition
  - average U.S. diet vs. healthful diet, 709*f*
  - calorie (cal), 18
  - carbohydrates, 709–710. *see also* Carbohydrates
  - catabolism of food, 718–719
  - diet foods, 782
  - fiber, 571
  - fiber supplements, 728
  - food label, 707, 708*f*
  - fruits and vegetables, 150
  - glycemic index (GI), 740
  - healthful diets, 103
  - heart-healthful diet, 714
  - high-protein diet, 621
  - juices and sports drinks, 225
  - lipids, 710–711. *see also* Lipids
  - Mediterranean diet, 103
  - milk, 632
  - minerals, 714–716
  - MyPlate, 707, 708*f*
  - organic foods, 331, 331*f*, 340
  - plant-based diet, 714
  - portion size, 714
  - processed meat, 650
  - proteins, 711, 711*f*. *see also* Proteins
  - RDIs, DRVs, and DVs, 707, 708*f*
  - sodium intake, 714
  - sugar-free foods and diabetes, 561
  - tart flavor of foods, 468
  - 2000-calorie diet, 707
  - 2015-2020 Dietary Guidelines, 709–710, 711
  - vitamins, 712, 713*t*
  - water, 210, 225
- Nutrition Facts label, 707, 708*f*
- Nutrition Labeling and Education act, 707
- Nutritionist/nutrition therapist, 706, 730
- Nuts and seeds, 765
- Nylon, 521, 521*f*

O

- octa-, 122*t*
- Octane, 345*t*, 358*t*
- Octet rule, 97, 99
- ODS. *See* Ozone-depleting substances (ODS)
- Ohm (Ω), A-1
- Oil of wintergreen, 391, 487*f*
- Oil spills, 205*f*, 358*f*
- Oils, 589. *See also* Fats and oils
- Okazaki, Reiji, 683
- Okazaki fragment, 682*f*, 683, 683*f*
- Oleic acid, 585, 586*f*, 586*t*, 606
- Oligosaccharide, 548*f*
- Olive oil, 606
- Omega-3 fatty acids, 586*t*, 587
- Omega-6 fatty acids, 586*t*, 587
- O.N. *See* Oxidation number (O.N.)
- Onions, 431*f*
- Opium, 526, 527, 527*f*
- Optically active molecule, 555

Optimum pH, 655, 655*t*
Optimum temperature, 654
Orange, 712*f*
Orange juice, 212*f*
Orbital. *See* Atomic orbital
Orbital overlap, 108, 108*f*
Organelle, 600, 600*t*
"organic," 331
Organic chemistry, 565
  defined, 331
  functional groups, 336–339
  physical makeup of Earth and moon, 332*f*
  studying tips, 334
Organic compound
  carbon, 331–332
  classes, 338*t*
  defined, 331
  functional groups, 338*t*
  inorganic compound, compared, 332–333, 333*t*
  IUPAC name, 346
  properties, 333*t*
Organic fertilizer, 331
Organic foods, 331, 331*f,* 340
Orientation effects, 241–242, 242*f*
Orlon, 387, 389*t*
Osmolarity, 222
Osmosis, 222, 222*f*
Osmotic pressure, 221–223
Osteoporosis, 54
Ovalbumin, 626
Over-the-counter iron supplements, 119
Over-the-counter pain-relieving creams, 463
Over-the-counter teeth whitening medications, 152
Oxalic acid, 468*f,* 480*t*
Oxaloacetate, 771
Oxidation
  alcohols, 418–421
  aldehydes and ketones, 452–455
  cysteine, 620
  defined, 142, 142*t*
  fatty acids, 767–770
  monosaccharides, 560–561
  oxidation process/reduction process, 142
  oxidizing agents/reducing agents, 144, 144*t*
β-oxidation, 767
Oxidation number (O.N.), 142, 142–143, 156
Oxidation number assignment rules, 142
Oxidation states, 142
Oxidative deamination, 776–777
Oxidative phosphorylation, 746–747, 747*f*
Oxidizing agent, 144, 144*t*
Oxidoreductases, 649*t*
Oxygen
  behavior, in response to heating, 126*t*
  fire or sparks, 241
  pulse oximetry, 800
  specific heat, 188*t*
  therapeutic uses of oxygen gas, 187
  transport within bloodstream, 794–797
Oxygen-17, 319
Oxygen molecules, 8, 11
Oxygen therapy, 140*f*
Oxyhemoglobin, 794, 795, 795*f*
Oxytocin, 624, 624*f,* 625*t*
Ozone, 127
Ozone-depleting substances (ODS), 127

P

p orbital, 74, 74*f*
p overlap, 390, 390*f*
P site, 693, 693*f,* 694, 694*f*
PA. *See* Physician's assistant (PA)
PABA (*p*-aminobenzoic acid), 480*f*
Pain Doctor, 463
Pain-relieving creams, 463
Palindrome, 697
Palmitic acid, 359, 481*t,* 586*t*
Palmitoleic acid, 586*t*
Panadol, 522
PANCE (Physician Assistant National Certifying Exam), 252
Pantothenic acid, 651*t,* 713*t*
Parachute, 521
Paraffin wax, 360
Paraffins, 360
Paramedic, 96, 130
Partial pressure, 180, 181
Particle accelerators, 319–320
Pascal (Pa), A-1
Pauli, Wolfgang, 78, 78*f*
Pauli exclusion principle, 78
Pauling, Linus, 334, 334*f,* 630
PCR. *See* Polymerase chain reaction (PCR)
Pediatric nurse, 762, 784–785
Penguins, 583*f*
Penicillin G, 657*t*
Penicillin V, 657*t*
Penicillinase, 653*t*
Penicillins, 656, 656*f,* 657*t*
penta-, 122*t*
Pentagon, 353
2-pentanamine, 512
Pentane, 345*t,* 346, 358*t,* 482*t*
n-pentane, 346
1-pentene, 380*t*
Pentose, 556*t*
Pentothal, 534*t*
Pepperoni, 650
Pepsin, 648, 655*t,* 660, 660*t*
Pepsinogen, 660*t*
Peptide bond, 621
Peptide linkage, 621
Peptides, 621–625
Percent, 209
Percentage yield, 155–156
Percentages, 30–31, 62–63
Perchlorate ion, 262
Perchloric acid, 262
Period, 71
Periodic law, 71
Periodic table
  classification on basis of electronic configurations, 84*f*
  common states of elements, 165*f*
  defined, 71
  diatomic covalent molecules, 119–120
  distinguishing electrons, 83*f*
  forms, 72*f*
  inner-transition elements, 84*f*
  melting and boiling points, 129
  metalloids, 86, 86*f*
  metals, 86, 86*f*
  noble gases, 84*f*
  nonmetals, 86, 86*f*
  property trends, 86–90
  representative elements, 84*f*
  transition elements, 84*f*
Periodic table group, 71, 76*f,* 76*t,* 77, 82
Personal care product developer, 198, 227–228
PET. *See* Polyethylene terephthalate (PET)
PET scan. *See* Positron emission tomography (PET) scan
Petroleum industry, 317
Petroleum jelly, 359
PGE$_2$, 607
PGF$_2$, 607
pH
  acidosis, 773, 801
  alkalosis, 801
  buffer control, 801–802
  calculating pH values, 267
  carboxylic acid, 483
  classifying acids and bases, 267
  death, 801
  defined, 266
  enzyme-catalyzed reactions, 654–655, 654*f*
  equations, 266
  Henderson-Hasselbalch equation, 290, 291
  indicators changing color, 286*f*
  isoelectric point, 619
  ketoacidosis, 773
  mixture of sodium citrate and citric acid, 487
  molarity, 270
  optimum, 655, 655*t*
  respiratory control, 802
  salts/water solutions, 289
  urinary control, 802–803
pH meter, 287*f*
Pharmacy technician, 478, 499
Phemerol, 519
Phenacetin, 531
Phenethylamine, 526
Phenol, 394, 397*t,* 409, 412, 425, 426. *See also* Phenols
Phenolase, 649*f*
Phenolphthalein, 289*f*
Phenols
  characteristics, 425
  defined, 409
  naming, 412
  parent compound (phenol), 394, 397*t,* 409, 412, 425, 426
  uses, 426–427
Phenyl group, 394
1-phenyl-2-propanol, 411
Phenylalanine, 397*t,* 617*t,* 691*t,* 711*t,* 782, 783*t*
4-phenylheptane, 394
Phenylketonuria (PKU), 781, 782
1-phenylpropane, 396
o-phenylphenol, 426
Phosphate buffer system, 803
Phosphate esters, 497–498, 562, 674, 675
Phosphatidylcholine, 595
Phosphodiester bonds, 676
Phosphoglycerides, 594–597, 601*f,* 763, 765*f*
Phospholipids, 594
Phosphoproteins, 628*t*
Phosphoric acid, 265, 281*t,* 282*f,* 283*t,* 291*t,* 497, 517
Phosphoric anhydride, 498
Phosphorous acid, 283*t*
Phosphors, 315
Phosphorus, 55–56, 87*f,* 715*t,* 716*f*
Phosphorus-containing acids, 265
Photosynthetic process, 317
Physical changes, 4, 6, 6*f*
Physical properties, 4, 87
Physical therapy assistant (PTA), 582, 607
Physical unit of radiation, 313
Physician Assistant National Certifying Exam (PANCE), 252
Physician's assistant (PA), 236, 252
Phytonutrients, 150
Pi (Π) bond, 377, 377*f,* 390*f*
Pickles, 654*f*
pico-, 14*t*
pK_a, 290, 291, 291*t*
PKU. *See* Phenylketonuria (PKU)
Planar representation, 340*f*
Plant-based diet, 714
Plants and drugs, 526
Plasma, 793, 793*f*
Plasmids, 698, 698*f*
Plaster of Paris, 277*t*
Plastic pollution in world's oceans, 489
Plexiglas, 387, 389*t*
Plutonium, 320
Plutonium-239, 324
Poison ivy, 426*f*
Polar covalent bond, 118, 120, 120*f*
Polar molecule, 121, 121*t,* 123
Poly (methyl methacrylate), 389*t*
Poly (vinyl acetate), 389*t*
Poly (vinyl chloride), 387, 389*t*
Polyacrylonitrile, 389*t*
Polyamides, 521–522
Polyatomic ions
  common, 123*t*
  defined, 111
  Lewis structures, 112–113
  shape, 114–118
  VESPR theory, 114–118
Polyatomic molecules, 8
Polycillin, 534*t*
Polycyclic aromatic compounds, 396–397
Polyester, 489
Polyethylene, 387, 389*t*
Polyethylene terephthalate (PET), 489, 490
Polyfunctional compound, 433–434
Polymer-based consumer products, 387*f*
Polymerase chain reaction (PCR), 683–684
Polymerization, 387
Polypeptide, 623
Polypeptide chain, 693–695
Polyphenols, 606
Polypropylene, 389*t*
Polyribosome, 695, 695*f*
Polysaccharides, 548*f*
  cellulose, 570–572
  defined, 548
  glycogen, 570
  mono/disaccharides, compared, 568*t*
  starch, 568–569
Polysome, 695
Polystyrene, 387*f,* 389*t,* 397
Polytetrafluoroethylene, 389*t*
Polyunsaturated, 382
Polyunsaturated fatty acids, 585, 586*t*
Polyvinyl chloride, 387*f*
Portion size, 714
Position of equilibrium, 247
Positron, 305, 306*t,* 308
Positron emission tomography (PET) scan, 308*f*
Potassium, 74, 715*t,* 716*f*
Potassium-38, 310
Potassium-40, 318
Potassium benzoate, 485
Potassium chloride, 278*f*
Potassium chromate, 124*f*
Potassium compounds, 124*f*
Potassium dichromate, 124*f*
Potassium permanganate, 124*f*
Potassium phosphate, 124*f*
Potassium salts, 591
Potential energy, 169, 169*f,* 186
PP$_i$. *See* Pyrophosphate (PP$_i$)
Prednisolone, 605
Preparing solutions of specific concentration, 212–216
Pressure
  defined, 171
  osmotic, 221–223
  partial, 180, 181
  units of, 172*t*
  vapor, 183, 184, 184*t,* 185
Pressure cooker, 185, 185*t,* 245
Priestley, Joseph, 145
Primary alcohol, 412, 413*t*
Primary amines, 511, 511*t,* 514, 519
Primary protein structure, 628–629
Procarboxypeptidase, 660*t*
Processed meat, 650
Products, 139
Proelastase, 660*t*
Proenzyme, 660
Progesterone, 464, 606
Prokaryotic cell, 600
Prolactin, 625*t*
Proline, 615*f,* 617*t,* 691*t,* 783*t*

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Promethium, 320
Propanal, 449*t*, 451*t*
Propanamide, 529
2-propanamine, 513
Propane, 341, 341*f*, 345*t*, 347*t*, 358*t*, 415
1,2-propanediol, 424, 425*t*
1,2,3-propanetriol, 411
Propanethiol, 431, 432
1,2,3-propanetriol, 424, 425*t*
Propanoates, 486*f*
Propanoic acid, 480*t*, 481, 482*t*
1-propanol, 413, 451*t*
2-propanol, 385, 413, 423, 425*t*
Propanone, 449*t*, 451*t*
Propene, 378, 380*t*, 385
1-propene-3-thiol, 431
Propionaldehyde, 449*t*
Propionic acid, 480*t*, 481*t*
Propofol, 412
Propolis, 361
Propyl alcohol, 410, 413
Propyl group, 346, 347*t*
Propylbenzene, 396
Propylene, 374
Propylene glycol, 357, 424, 425*t*
Prostaglandins, 606–607
Prosthetic groups, 627
Protein backbone, 628, 633*f*
Protein synthesis, 693–695
Protein turnover, 774
Proteins, 614–644, 711. *See also* Amino acids
  acid-base properties, 626
  α-helix, 630, 630*f*, 631*f*
  amide hydrolysis, 533
  antibodies, 626
  backbone, 628, 633*f*
  β-pleated sheet, 631, 631*f*
  classification, 627–628
  complete, 711
  conjugated, 627–628, 628*t*
  defined, 623
  denaturation, 636–637, 638*t*
  disulfide linkages, 432
  fibrous, 627, 627*f*
  functions, 626–627, 627*t*
  globular, 627
  half-life, 774–775
  high-protein diet, 621
  hydrolysis, 636
  hydrogen bonding, 629, 632–633
  natural polyamides, 522
  primary structure, 628–629
  quaternary structure, 634, 635*f*
  R-group interactions, 633, 634*t*
  RDI, 711, 711*t*
  secondary structure, 629–631
  simple, 627
  size, 625, 625*t*
  tertiary structure, 632–634
  translation (protein synthesis), 693–695
  turnover rate, 774
  visualizing protein structure, 636
Proteinuria, 799*t*
Prothrombin, 660*t*
Proton pump inhibitors, 284
Protons, 50, 50*t*
Psyllium, 727
PTA. *See* Physical therapy assistant (PTA)
Pure solvent, 219*t*
Pure substance, 10
  characteristics, 10, 125*t*
  crystal lattice, 125
  defined, 9
  elements/compounds, 11, 12*f*
  heating, 126*t*
  homogeneous matter, 10
Pure water, 9
Purine, 674, 674*f*, 775
PVC, 389*t*
Pyran, 429
Pyranose ring, 558, 559
Pyridoxal, 651*t*
Pyridoxamine, 651*t*
Pyridoxine, 651*t*, 713*t*
Pyrimidine, 674, 674*f*, 775
Pyrophosphate (PP_i), 721, 722
Pyruvate
  fates of, 741–742, 742*f*
  oxidation of Acetyl CoA, 741
  reduction to ethanol, 742
  reduction to lactate, 741–742

Q
Quantitative measurements, 13
Quantum mechanical model, 73, 74
Quaternary ammonium salts, 518–519, 519*f*
Quaternary protein structure, 634, 635*f*
Quinine, 527

R
R-group interactions, 633, 634*t*
R groups (side chains), 615, 616, 617*t*, 628, 630
Racing cars, 422, 422*f*
Rad (D), 313, 314*t*
Radiation sickness, 311, 326
Radicals, 311
Radioactive dating, 317–318
Radioactive decay, 206
Radioactive decay curve, 310*f*
Radioactive nuclei, 305–306
Radioactive tracers, 315–316, 317, 317*f*
Radioactivity and nuclear processes, 304–329
  absorbing radiation by shielding, 312
  acute radiation syndrome, 311
  bombardment of nuclei, 319–320, 326
  breeder reaction, 323
  chain reactions, 321–322, 322*f*
  cyclotron, 319–320, 319*f*
  daughter nucleus, 307
  detecting radiation, 314–315
  diagnostic radiation, 308*f*, 314
  distance and radiation intensity, 312, 313
  electron capture, 308
  equations for nuclear reactions, 306–309, 320–321
  free radicals, 311
  half-life, 309–311
  health effects of radiation, 311–313
  induced nuclear reactions, 318–321
  inverse square law of radiation, 312
  measurement units of radiation, 313–314, 314*t*
  medical uses of radioisotopes, 315–316
  nonmedical uses of radioisotopes, 317–318
  nuclear energy, 321–325
  nuclear fission, 321, 325
  nuclear fusion, 324, 325
  nuclear power plants, 324, 324*f*
  particle accelerators, 319–320
  penetrating abilities of radiation rays, 312, 312*f*
  radioactive dating, 317–318
  radioactive decay, 206
  radioactive decay curve, 310*f*
  radioactive nuclei, 305–306
  thermonuclear reaction, 324
  tracers, 315–316, 317, 317*f*
  types of emitted radiation, 305, 305*f*, 306*t*
  writing symbols for particles, 306–307
Radioisotope
  defined, 306
  medical uses, 315–316
  nonmedical uses, 317–318
  tracers, 315–316, 317, 317*f*
Radiologic technician, 70, 91
Radiologist, 70, 91
Radiopharmaceuticals, 325
Radon, 318
Radon-222, 318
Radon detectors, 318
RDIs. *See* Reference Daily Intakes (RDIs)
Reactants, 139
Reaction card file, 385
Reaction map
  alcohols, 423
  aldehydes and ketones, 460
  alkenes, 388
  amines, 525
  carboxylic acids, 496
  triglycerides, 594
Reaction mechanism, 240
Reaction rates and equilibrium, 236–259
  chemical equilibrium, 246–247
  energy diagram, 242–243, 242*f*
  equilibrium constant, 247, 248–249, 250
  equilibrium expression, 247, 248
  factors that influence equilibrium position, 250–251
  factors that influence reaction rates, 243–245
  Ionic equilibrium equations, 273
  Le Châtelier's principle, 250–251, 252
  molecular collisions, 240–242
  position of equilibrium, 247
  reaction rates, 239
  spontaneous and nonspontaneous processes, 237–238
  state of equilibrium, 246
Reaction yields, 155–156
Reactions. *See* Chemical reactions
Real gases, 180
Reclamation site, 190
Recombinant DNA, 696–699
Red meat, 650
Redox combination reaction, 146
Redox reactions, 141–145
Reduce, Reuse, Recycle, and Refuse (four R's), 359
Reducing agent, 144, 144*t*
Reducing sugars, 560–561
Reduction, 142, 142*t*
Reduction process, 144
Reference Daily Intakes (RDIs), 707
Registered nurse (RN), 646, 665
Relative mass, 52–54
Relative specificity, 648
Rem, 313, 314*t*
Renal threshold, 738
Replacement reaction, 146–148
Replication, 680–684
Replication fork, 680, 682*f*
Representative elements, 83, 84*f*
Resiniferatoxin (RTX), 463
Respiratory acidosis, 804–805, 805*t*
Respiratory alkalosis, 804, 805*t*
Respiratory control of blood pH, 802
Respiratory therapist (RT), 260, 292
Restriction enzyme, 696–698
Retinol, 713*t*
Reversible inhibition, 656–660, 662
Reye's syndrome, 522
Rhodopsin, 626, 626*f*
Rhubarb, 468*f*
Riboflavin, 397*t*, 651*t*, 713*t*
Ribonucleic acid. *See* RNA
Ribose, 547, 563
β-D-ribose, 563
D-ribose, 674
Ribosomal RNA (rRNA), 685, 685*t*
Ribulose, 556
Richter, Jeremias, 151*f*
Ripening of fruit, 245
RN. *See* Registered nurse (RN)
RNA
  anticodon, 685
  codon, 691, 691*t*
  D-ribose (sugar component), 674
  defined, 673
  DNA, contrasted, 684
  heterogeneous nuclear RNA (hnRNA), 689, 689*f*
  messenger RNA (mRNA), 684–685, 685*t*
  mRNA codons for each amino acid, 691*t*
  non-coding RNA (ncRNA), 687
  primary structure, 684
  ribosomal RNA (rRNA), 685, 685*t*
  secondary structure, 684
  transcription (RNA synthesis), 688–689
  transfer RNA (tRNA), 685, 685*t*, 686*f*
  translocation, 694, 694*f*
  writing RNA sequences, 688–689
RNA polymerase, 688
Rocket repellant, 139*f*
Roentgen (R), 313, 314*t*
Roentgen, Wilhelm, 314
Rounding, 25
Royal jelly, 361
rRNA. *See* Ribosomal RNA (rRNA)
RT. *See* Respiratory therapist (RT)
RTX. *See* Resiniferatoxin (RTX)
Rubbing alcohol, 211*f*, 423
Rubidium-79, 310
Rubidium-84, 310
Rulers, 23*f*
Rusting of iron, 237*f*
Rutherford, Ernest, 319, 321

S
(s), 139
s orbital, 74, 74*f*
Saccharin, 561
Salad dressing, 224, 226
Salami, 650
Salmon, 587*f*, 765
Salt, 74
Salt bridge, 632, 633*f*
Salts, 276–280
  anion/cation, 277
  defined, 276
  equivalent of salt, 278, 279–280
  hydrates, 277, 277*t*
  hydrolysis reactions, 288–289
  naming, 277
  water of hydration, 277
Saponifiable lipids, 583
Saponification, 495, 591, 592
Saponification reactions, 495–496
Saran Wrap, 388
Sardines, 765
Saturated fatty acids, 585, 586*f*, 586*t*, 589*f*
Saturated hydrocarbon, 339, 339*f*. *See also* Alkanes
Saturated solution, 202
Scanning tunneling microscope (STM), 50*f*
Schrödinger, Erwin, 73
Schrödinger's quantum mechanical model, 73, 74
Scientific calculator. *See* Calculator
Scientific models, 7
Scientific notation, 19, 22
Scintillation, 315
Scintillation counter, 315
Sebum, 594
Second ionization energy, 89
Secondary alcohol, 412, 413*t*
Secondary amines, 511, 511*t*, 514, 519
Secondary protein structure, 629–631
Seesaw (teeter-totter), 53–54
Selenium, 715*t*

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Self-ionization of water, 265–267
Semiconservative replication, 680
Serine, 596, 617*t*, 691*t*, 775*t*, 783*t*
Serotonin, 511, 524, 775*t*
Serotonin blockers, 525
Sex hormones, 464, 605–606
Shape, 166, 167*t*
Shaving cream, 223
Shell
    defined, 73
    electron occupancy of shells, 76*t*
    fourth shell of an atom, 75*f*
    relative energies and electron-filling order, 79*f*
    subshells, orbitals, and electrons, relationship with, 75*t*
    valence, 76, 77
Shell model, 76–77
Shortenings, 592, 592*f*
Shroud of Turin, 318*f*
SI units, 13, A-1
Sickle-cell disease, 629
Side chains (R groups), 615, 616, 617*t*, 628, 630
Side reaction, 155
Sigma bonds, 377, 377*f*
Significant figures
    addition and subtraction, 27
    concept summary, 36
    defined, 24
    leading, buried, trailing zeros, 24, 24*f*
    multiplication and division, 26
Silent Spring (Carson), 381*f*
Silicon, 51, 715*t*
Silk, 522
Silver, 637
Simple carbohydrates, 709
Simple ion, 99
Simple lipids, 583
Simple proteins, 627
Single-replacement reaction, 146–147, 147*f*
Skin moisturizers, 357
Skunks, 431, 431*f*
Smog, 127
Smoke, 223
Smoke detectors, 306*f*
Soap, 225–226, 275*f*, 486*f*, 591, 592*f*
Soap making, 591
Soapless centuries, 591
Soda, 225
Soddy, Frederick, 321
Sodium, 74, 82, 714, 715*t*, 716*f*
Sodium acetate, 289*f*, 485
Sodium benzoate, 486
Sodium chloride, 289
Sodium ethanoate, 485
Sodium glycocholate, 603
Sodium hydroxide, 271*t*, 290*f*
Sodium salts, 591
Sodium stearate, 486
Sodium thiosulfate, 656
Soft soaps, 591
Solids, 166*f*, 167*t*, 169–170, 170*f*
Solubility, 200–204, 206
Soluble substance, 201
Solute, 199, 200
Solute dissociation, 221
Solute solubilities, 200–204, 206
Solution boiling and freezing points, 219–221
Solution classifications and calculations, 266–267
Solution concentrations, 208–212
Solution preparation, 212–216
Solution properties, 218–223
Solution reaction calculations, 214–216
Solution stoichiometry, 216–218
Solutions and colloids, 10, 10*f*, 198–235
    colligative properties, 219, 219*t*, 221
    colloids, 223–226
    dialysis, 226–227
    diffusion, 221, 221*f*
    dilution, 214–216
    dissolving polar solute in water, 205
    dissolving rate, 207
    electrical conductivity of solutions, 218–219
    electrolytes/nonelectrolytes, 218*f*, 219
    emulsifying/stabilizing agents, 224
    exothermic/endothermic solution process, 207, 207*f*
    gels, 223
    molarity, 208–210
    osmolarity, 222
    osmotic pressure, 221–223
    physical states of solutions, 199–200
    saturated/supersaturated solution, 202
    soaps and detergents, 225–226
    solubility, 200–204, 206
    soluble/insoluble substance, 201
    solute dissociation, 221
    solute/solvent, 199, 200
    solution, defined, 10, 10*f*, 199
    solution boiling and freezing points, 219–221
    solution concentrations, 208–212
    solution preparation, 212–216
    solution process, 204–207
    solution properties, 218–223
    solution reaction calculations, 214–216
    solution stoichiometry, 216–218
    Tyndall effect, 223
    volume/volume percent, 211
    weight/volume percent, 211
    weight/weight percent, 209
Solutions to Learning Checks, C-1 to C-22
Solvent, 199, 200
Somatostatin, 625*t*
Sonographer, 736, 755
Sorbitol, 561
Souring of milk, 245
Soybean, 382
sp^2 hybridization of carbon, 377*f*
sp^2 overlap, 377, 377*f*
Space-filling model, 340*f*, 341*f*, 586*f*
Spearmint, 555*f*
Specific heat, 186–190
Spectator ions, 149
"Speed," 526
Spherical configuration, 323, 323*f*
Sphingolipids, 597–600
Sphingomyelin, 597, 598, 600*t*
Sphingosine, 597, 598
Sphygmomanometer, 174
Spinach, 468*f*
Spoiling of food, 245
Spontaneity, 238
Spontaneous process, 237–238
Sports drinks, 225
Stabilizing agent, 224
Stable substance, 238
Stainless steel, 199*f*
Standard atmosphere, 172
Standard boiling point, 184
Standard conditions (STP), 178
Standard position, 19–20
Starch, 568–569, 709
Starch-iodine complex, 569*f*
Start codon, 691*t*, 692
State of equilibrium, 246
States of matter, 164–197
    Avogadro's law, 178
    boiling point, 184–185, 185*f*, 185*t*
    Boyle's law, 175
    changes in state, 182
    characteristics, 166*f*
    Charles' law, 175
    combined gas law, 175
    condensation, 183
    Dalton's law, 180, 181*f*
    diffusion/effusion, 181
    energy, 186–190
    evaporation, 183, 183*f*
    gas laws, 171–174
    gases, 166*f*, 167*t*, 170–171, 170*f*
    Graham's law, 181–182
    ideal gas law, 178–180
    kinetic molecular theory of matter, 168–169, 173
    liquids, 166*f*, 167*t*, 170, 170*f*
    melting point, 185
    observed properties of matter, 166–168
    pressure, temperature, and volume relationships, 174–177
    real gases/ideal gases, 180
    solids, 166*f*, 167*t*, 169–170, 170*f*
    specific heat, 186–190
    sublimation, 185
Static electricity, 241
Statues, 272*f*
Stearic acid
    candles, 481
    carboxylic acid salt, 486
    energy produced by oxidation, 770*t*
    esterification reaction of stearic acid and glycerol, 588
    formula/common sources, 586*t*
    melting point, 585, 586*t*
    name, 479
    β-oxidation, 768*f*
    physical properties, 481*t*
    space-filling model, 586*f*
Stem names, 104, 104*t*
Stereochemical specificity, 648
Stereoisomer, 355, 552
Stereoisomerism, 355
Sterile processing technician, 2, 35
Steroid hormones, 604–606
Steroids, 602–604
STM. *See* Scanning tunneling microscope (STM)
Stoichiometry, 151
Stop codon, 691*t*, 692, 695
STP. *See* Standard conditions (STP)
Strassman, Fritz, 321
Stratosphere, 127
Strawberries, 712*f*
Striking of kitchen match, 246
Strong acids and strong bases, 281
Strong electrolytes, 218*f*, 219
Strontium, 76*f*
Structural formula, 338*t*, 343, 353*t*, 465*t*. *See also* Condensed structural formula; Expanded structural formula
Structural isomers, 335, 344
Study Tools boxes
    ATP calculations, 752, 773
    biomolecules, 565
    bioprocesses, 722
    calculations (formula problems/factor-unit problems), 32
    convention hotels analogy, 81
    enzyme inhibitors, 662
    gas laws, which one to use, 189
    Le Châtelier's principle, 250–251
    molarity calculations, 210
    mole calculations, 64
    organic chemistry, 334
    oxidation numbers, 156
    polar/noonpolar molecules, 123
    reaction card file, 385
    reaction map for alcohols, 423
    reaction map for aldehydes and ketones, 460
    reaction map for alkenes, 388
    reaction map for amines, 525
    reaction map for carboxylic acids, 496
    reaction map for triglycerides, 594
    replication, transcription, and translation, 692
    visualizing protein structure, 636
    writing reactions of acids, 276
Styrene, 397*t*
Styrofoam, 389*t*
Subatomic particles, 50, 50*t*
Subcritical mass, 323*f*
Sublimation, 185
Subshell
    defined, 73
    designation, 75*t*
    filling order, 80, 80*f*
    fourth shell of an atom, 75*f*
    relative energies and electron-filling order, 79*f*
    s and *p*, 74
    shells, orbitals, and electrons, relationship with, 75*t*
Subshell designation, 75*t*
Subshell filling order, 80, 80*f*
Substitution reaction, 146
Substrate, 648, 649
Subunit, 634
Succinate, 657
Succinate dehydrogenase, 655*t*, 657
Sucralose, 561
Sucrase, 655*t*
Sucrose, 558*t*, 567, 568*t*
Sugar, 557
    added, 710
    invert, 558*t*, 567
    reducing, 560–561
    relative sweetness, 558*t*
Sugar alcohols, 561
Sugar-free foods, 561
Sugar-phosphate backbone, 678
Sugary foods, 740
Sulfa drugs, 656, 657–659
Sulfanilamide, 657, 658, 658*f*
Sulfhydryl group, 430, 725*f*
Sulfur, 59–60, 243, 715*t*, 716*f*
Sulfur trioxide, 146
Sulfuric acid, 146, 271*t*, 281*t*, 517
Sulfurous acid, 281*t*, 291*t*
Sun, 324*f*, 716
Sunflower seeds, 765
Sunflowers, 589*f*
Suntan, 395, 451
Supercritical mass, 323, 323*f*
Supercritical reaction, 322, 322*f*
Supersaturated solution, 202, 205
Surface catalyst, 245
Symbols and formulas, 47–49
Synapse, 523, 523*f*
Synaptic terminals, 523, 523*f*
Synthesis reaction, 146

T

T_3, 775*t*
T_4, 775*t*
Table salt, 276
Tanning lotions and creams (chemical tans), 451
Tanning salons, 395
Taurine, 775*t*
Taxol, 409*f*
Tay-Sachs disease, 600*t*
TCA. *See* Tricarboxylic acid cycle (TCA)
Tea, 241, 527*f*
Technetium, 320
Technetium-99m, 325
Technetium-99m-MDP (methylene diphosphonate), 325
Teeter-totter (seesaw), 53–54
Teeth whitening, 152
Teflon, 387, 389*t*
Temperature
    body functions, 19
    enzyme-catalyzed reactions, 654, 654*f*
    equilibrium constant, 250, 250*f*
    optimum, 654

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

  position of equilibrium, 250, 250*f*
  reaction rates, 245
  solute solubilities, 203–204, 203*f*
  states of matter, 174–177
  vapor pressure of water, 184*t*
  water density, 128*t*
Temperature scales
  Celsius scale, 16, 17*f*
  converting Celsius into Fahrenheit, 17
  converting Celsius into Kelvin, 17, 173–174
  converting Fahrenheit into Celsius, 17
  converting Kelvin into Celsius, 17, 173–174
  Fahrenheit scale, 16, 17*f*
  Kelvin scale, 16, 17*f*
Termination factor, 695
Tertiary alcohol, 412, 413*t*
Tertiary amines, 511, 511*t*, 514, 519
Tertiary protein structure, 632–634
Terylene, 490
Testes, 605
Testosterone, 464, 605
tetra-, 122*t*
Tetracycline, 152
Tetrahedral structure, 340*f*, 354
Tetrahydrocannabinol, 434
Tetrose, 556, 556*t*
The Ocean Cleanup, 489
Theoretical yield, 155
Theory of relativity, 321
Therapeutic radioisotopes, 315–316, 326
Thermal expansion, 166, 167*t*
Thermonuclear reaction, 324
Thiamin, 651*t*, 713*t*
Thioester bond, 725
Thiols, 430–433
Thiopental, 534*t*
Thirst mechanism, 800, 800*f*
Thorium, 307
Thorium-232, 325
Thorium-234, 307
Three-Mile Island, 324
3-D printers, 378
3’ end, 676, 685, 686*f*, 693*f*, 694*f*
Threonine, 617*t*, 691*t*, 711*t*, 783*t*
Throat lozenges, 426
Throat sprays, 425*f*
Thrombin, 660*t*
Thymine, 674, 674*f*
Thyroid cancer, 316
Thyroid gland, 316
Thyroid scan, 316*f*
Thyrotropin, 626
Thyroxine (T_3 and T_4), 775*t*
Tin, 715*t*
Titanic, sinking of, 128*f*
Titration, 285–288
Tobacco smoke, 397
Tocopherol, 713*t*
Tollens’ reagent, 454, 455
Toluene, 394, 397*t*
Tooth enamel, 152
Toothpaste, 425*f*
Torr, 172, 172*t*
Torricelli, Evangelista, 171
Total ionic equation, 148
Total mass, 56
Trace minerals, 714, 715*t*
Tracers, 315–316, 317, 317*f*
Trailing zeros, 24, 24*f*
trans-, 356
Trans fats, 594
Trans fatty acids, 594
Transaminase, 776, 783, 784
Transamination, 776–777, 784
Transcription, 687, 688–689
Transfer RNA (tRNA), 685, 685*t*, 686*f*. *See also* RNA
Transferases, 649*t*
Transferrin, 627
Transition element, 84, 84*f*
Translation, 687, 693–695
Translocation, 694, 694*f*
Transpeptidase, 656
Transuranium elements, 320
tri-, 122*t*
Triacylglycerols, 588
Triatomic molecules, 8
2,4,6-tribromophenol, 412
Tricarboxylic acid cycle (TCA), 743
1,2,4-trichlorobenzene, 395
Triester, 497
Triethylamine, 514*t*
Triethylammonium acetate, 517
Triethylmethylammonium chloride, 518
Triglycerides
  defined, 588
  digestion and absorption, 764, 786
  important dietary sources of energy, 763
  oils/oil-fried foods, 710, 710*f*
  reaction map, 594
  relative amounts in lipoproteins, 766*f*
  writing structures, 588–589
Trimethylamine, 514*t*
Triols, 411
Triose, 556*t*
Triphosphates, 498
Triple bonds, 109
Triprotic acid, 282, 283*t*
Trisodium phosphate (TSP), 277*t*
Trivial or common names, 345
tRNA. *See* Transfer RNA (tRNA)
Troposphere, 127
Trustworthiness of websites, 34
Trypsin, 648, 660, 660*t*
Trypsinogen, 660, 660*t*
Tryptophan, 524, 617*t*, 691*t*, 711*t*, 775*t*, 783*t*
Tubular configuration, 323, 323*f*
Tuna, 765
Turnover number, 652, 653*t*
2015-2020 Dietary Guidelines, 709–710, 711
Tylenol, 522
Tyndall effect, 223
Tyrosine, 524, 617*t*, 691*t*, 775*t*, 783, 783*t*

U

Ultraviolet (UV) radiation, 395, 480*f*
Universal gas constant, 178
Unpaired electrons, 78, 79–80
Unsaturated fatty acids, 585, 586*f*, 589*f*
Unsaturated hydrocarbons, 372–402
  aliphatic compounds, 392
  alkenes. *see* Alkenes
  alkynes, 338*t*, 339*f*, 373, 390–391
  aromatics. *See* Aromatic compounds
  defined, 373
Uracil, 674, 674*f*
Uranium-235, 321, 322, 324
Uranium-238, 323, 325
Urea, 55*f*, 357
Urea cycle, 778–780
Urease, 655*t*
Urinary control of blood pH, 802–803
Urine, 798, 799, 799*t*
Urine specimen, 798
USAJobs.gov, 64
UV radiation. *See* Ultraviolet (UV) radiation

V

Valence shell, 76, 77
Valence-shell electron, 90, 98
Valence-shell electron-pair repulsion (VESPR) theory, 114–118
Valeric acid, 481*t*
Valine, 617*t*, 691*t*, 711*t*, 783*t*
Valium, 534*t*
Vanadium, 715*t*
Vanilla ice cream, 464*f*
Vanilla planifolia, 391*f*
Vanillin, 465*t*
Vanilloids, 463
Vapor pressure, 183, 184, 184*t*, 185, 219, 219*t*
Vaporization, 183
Vaseline, 359
Vasopressin, 624, 624*f*, 625*t*, 800, 801
Vector, 698
Vegetable oils, 378*f*, 382, 589. *See also* Fats and oils
Vegetables and fruits, 150
Very-low-density lipoprotein (VLDL), 766*f*
VESPR theory, 114–118
Vicks VapoRub, 416
Vinegar, 479*f*
Vinethene, 430
Vinyl chloride, 387, 388
Vinylidene chloride, 388
Vital force theory, 331
Vitamin A, 713*t*
Vitamin B_1, 651*t*, 713*t*
Vitamin B_2, 651*t*, 713*t*
Vitamin B_3, 651*t*
Vitamin B_6, 651*t*, 713*t*
Vitamin B_{12}, 651*t*, 713*t*
Vitamin C, 712*f*, 713*t*
Vitamin D, 713*t*
Vitamin E, 713*t*
Vitamin K, 713*t*
Vitamins, 712, 713*t*
VLDL. *See* Very-low-density lipoprotein (VLDL)
Volt (V), A-1
Volume, 14, 15
%(v/v), 211
Volume/volume percent, 211

W

Walnuts, 765
Washing soda, 277*t*
Water
  angularity of water molecules, 128
  boiling point, 185*f*, 185*t*
  chemical formula, 61
  covalent bonding, 109*t*
  healthy choice of fluid intake, 210
  heating, 126*t*
  human body, 114*f*
  neutral solution, 265*f*
  normal values for water entry and exit, 800*t*
  polar water molecule, 127*f*
  self-ionization, 265–267
  specific heat, 188*t*
  thirst mechanism, 800, 800*f*
  vapor pressure of water at various temperatures, 184*t*
  water density as function of temperature, 128*t*
Water-soluble vitamins, 712, 713*t*
Watson, James D., 678
Watson-Crick three-dimensional structure, 678, 678*f*, 680
Watt (W), A-1
Wax, 583*f*, 594, 594*f*
Weak acids and bases, 281
Weak electrolytes, 218*f*, 219
Websites
  helpful/accurate sites, 34
  sites to be avoided, 34
Weighing, 4
Weight, 4
Weight/volume percent, 211
Weight/weight percent, 209
Whipped cream, 487
White phosphorus, 243
Wildlife technician, 46, 64
Wintergreen, 391, 487*f*
Wöhler, Friedrich, 331
Wöhler’s urea synthesis, 331
Wood alcohol, 422
Wool, 522
%(w/v), 211
%(w/w), 209
World War II, 323

X

X-ray, 314
Xylitol, 557*f*
Xylose, 558*t*

Y

Yonath, Ada, 685*f*

Z

Zephiran, 519
Zephiran chloride, 519
Zinc, 715*t*
Zinc 10-undecylenate, 486
Zinc-containing lozenges, 85
Zwitterions, 618–620
Zymogen, 660, 660*t*

Copyright 2022 Cengage Learning. All Rights Reserved. May not be copied, scanned, or duplicated, in whole or in part. Due to electronic rights, some third party content may be suppressed from the eBook and/or eChapter(s). Editorial review has deemed that any suppressed content does not materially affect the overall learning experience. Cengage Learning reserves the right to remove additional content at any time if subsequent rights restrictions require it.

Table of Atomic Weights and Numbers

Name	Symbol	Atomic Number	Atomic Weight	Name	Symbol	Atomic Number	Atomic Weight
Actinium	Ac	89	(227)	Mendelevium	Md	101	(260)
Aluminum	Al	13	26.98	Mercury	Hg	80	200.6
Americium	Am	95	(243)	Molybdenum	Mo	42	95.96
Antimony	Sb	51	121.8	Moscovium	Mc	115	(288)
Argon	Ar	18	39.95	Neodymium	Nd	60	144.2
Arsenic	As	33	74.92	Neon	Ne	10	20.18
Astatine	At	85	(210)	Neptunium	Np	93	(237)
Barium	Ba	56	137.3	Nickel	Ni	28	58.69
Berkelium	Bk	97	(247)	Nihonium	Nh	113	(284)
Beryllium	Be	4	9.012	Niobium	Nb	41	92.91
Bismuth	Bi	83	209.0	Nitrogen	N	7	14.01
Bohrium	Bh	107	(270)	Nobelium	No	102	(259)
Boron	B	5	10.81	Oganesson	Og	118	(294)
Bromine	Br	35	79.90	Osmium	Os	76	190.2
Cadmium	Cd	48	112.4	Oxygen	O	8	16.00
Calcium	Ca	20	40.08	Palladium	Pd	46	106.4
Californium	Cf	98	(251)	Phosphorus	P	15	30.97
Carbon	C	6	12.01	Platinum	Pt	78	195.1
Cerium	Ce	58	140.1	Plutonium	Pu	94	(244)
Cesium	Cs	55	132.9	Polonium	Po	84	(209)
Chlorine	Cl	17	35.45	Potassium	K	19	39.10
Chromium	Cr	24	52.00	Praseodymium	Pr	59	140.9
Cobalt	Co	27	58.93	Promethium	Pm	61	(145)
Copernicium	Cn	112	(285)	Protactinium	Pa	91	231.0
Copper	Cu	29	63.55	Radium	Ra	88	(226)
Curium	Cm	96	(247)	Radon	Rn	86	(222)
Darmstadtium	Ds	110	(281)	Rhenium	Re	75	186.2
Dubnium	Db	105	(268)	Rhodium	Rh	45	102.9
Dysprosium	Dy	66	162.5	Roentgenium	Rg	111	(280)
Einsteinium	Es	99	(252)	Rubidium	Rb	37	85.47
Erbium	Er	68	167.3	Ruthenium	Ru	44	101.1
Europium	Eu	63	152.0	Rutherfordium	Rf	104	(265)
Fermium	Fm	100	(257)	Samarium	Sm	62	150.4
Flerovium	Fl	114	(289)	Scandium	Sc	21	44.96
Fluorine	F	9	19.00	Seaborgium	Sg	106	(271)
Francium	Fr	87	(223)	Selenium	Se	34	78.96
Gadolinium	Gd	64	157.3	Silicon	Si	14	28.09
Gallium	Ga	31	69.72	Silver	Ag	47	107.9
Germanium	Ge	32	72.63	Sodium	Na	11	22.99
Gold	Au	79	197.0	Strontium	Sr	38	87.62
Hafnium	Hf	72	178.5	Sulfur	S	16	32.07
Hassium	Hs	108	(277)	Tantalum	Ta	73	180.9
Helium	He	2	4.003	Technetium	Tc	43	(98)
Holmium	Ho	67	164.9	Tellurium	Te	52	127.6
Hydrogen	H	1	1.008	Tennessine	Ts	117	(294)
Indium	In	49	114.8	Terbium	Tb	65	158.9
Iodine	I	53	126.9	Thallium	Tl	81	204.4
Iridium	Ir	77	192.2	Thorium	Th	90	232.0
Iron	Fe	26	55.85	Thulium	Tm	69	168.9
Krypton	Kr	36	83.80	Tin	Sn	50	118.7
Lanthanum	La	57	138.9	Titanium	Ti	22	47.87
Lawrencium	Lr	103	(262)	Tungsten	W	74	183.8
Lead	Pb	82	207.2	Uranium	U	92	238.0
Lithium	Li	3	6.94	Vanadium	V	23	50.94
Livermorium	Lv	116	(293)	Xenon	Xe	54	131.3
Lutetium	Lu	71	175.0	Ytterbium	Yb	70	173.0
Magnesium	Mg	12	24.31	Yttrium	Y	39	88.91
Manganese	Mn	25	54.94	Zinc	Zn	30	65.38
Meitnerium	Mt	109	(276)	Zirconium	Zr	40	91.22

A value in parentheses is the mass number of the isotope of longest half-life for radioactive elements.